

Global Climate Change and California: Potential Implications for Ecosystems, Health, and the Economy

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to \$62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

What follows is the final report for the [Contract Name,] 500-97-043, conducted by the Electric Power Research Institute. The report is entitled Global Climate Change and California: Potential Implications for Ecosystems, Health, and the Economy. This project contributes to the Energy-Related Environmental Research program.

For more information on the PIER Program, please visit the Commission's Web site at: <http://www.energy.ca.gov/research/index.html> or contact the Commission's Publications Unit at 916-654-5200.

Abstract

This project is the most detailed study ever undertaken on the potential effect of climate change on California. This work examines a broad array of potentially affected sectors as well as the interactions between climate change and increased population, economic growth, and technological change. It considers a wide range of climate change scenarios, ranging from warmer and much wetter to warmer and much drier. Most climate models estimate that precipitation will increase.

Climate change is likely to have substantial impacts on California. The location of natural vegetation will change dramatically. Productivity could increase under wetter conditions and biodiversity could be reduced under drier conditions. The combined effects of climate change and urbanization on vegetation could adversely affect some critical systems. Timber production may initially increase and then decrease, but producers and consumers may be more affected by changes in global timber prices.

Higher temperatures will cause the snowpack to melt earlier in the year, increasing flood risks. Changes in the water supply are very sensitive to changes in precipitation. Agriculture will most likely demand more water, although population and economic growth will decrease the sector's allocation of water. Climate change could affect agriculture more favorably in northern California than in the south, but changes in technology may have a far greater impact statewide.

Energy expenditures are projected to rise significantly. The costs involved in protecting coastal resources may rise as well, but by much smaller amounts. Finally, impacts on human health will be very sensitive to changes in climate variability.

Keywords: climate change, California, impacts, vulnerability, terrestrial ecosystems, timber, agriculture, water, human health, energy

Executive Summary

Introduction

The world's climate is changing as a result of increased atmospheric concentrations of greenhouse gases, and this could significantly affect California. It is important to examine the potential impacts of climate change on California not only because of the state's size and geographic and biological diversity, but also because much of its well-being is tied to its natural resources. California produces more than one-eighth of total U.S. economic output, which makes it the fifth or sixth largest economy in the world. It contains the greatest diversity of species of any state. Its climate is quite varied, but is also known around the world for its mild and desirable qualities. The development of much of the state would have been impossible without the massive engineering effort to capture and transfer water from the mountains and from neighboring states to populated areas.

This report presents the assumptions, approaches, and results of the most detailed assessment of climate change impacts on California conducted to date. This research was initiated and primarily funded through the California Energy Commission's (Commission) Public Interest Energy Research (PIER) program. The Electric Power Research Institute (EPRI) provided significant cofunding and assisted in research management.

This study is the most integrated and detailed quantitative assessment of the potential impacts of climate change on California ever conducted. Even with such detail, many potential impacts or interrelationships were not examined, and simplifying assumptions were made about baseline conditions and relationships between sectors and climate. As such, results should be interpreted for what insight they provide about the sensitivity of certain sectors in California to climate change.

This project was designed to help California natural resource managers and other policy makers better understand the potential effects of climate change on the state. Indeed, the ultimate goal of the studies is to quantify the impacts of climate change for California and make available information that natural resource policy makers can use to develop adaptive policies. This focus differs from that of earlier Commission climate publications, which have focused on emission inventories and on policies and measures to reduce the greenhouse gas emissions implicated in climate change.

Project Approach

The structure of the project is displayed in Figure 1. The first step was the creation of scenarios of climate change and socioeconomic conditions (population, income, and land use). California's climate and society will both change substantially during this century. We have some idea what those changes will be, but we cannot predict precisely what will happen. So we use plausible scenarios to capture a reasonable range of potential future conditions. Scenarios of socioeconomic change and climate change were developed in consultation with experts in public workshops.

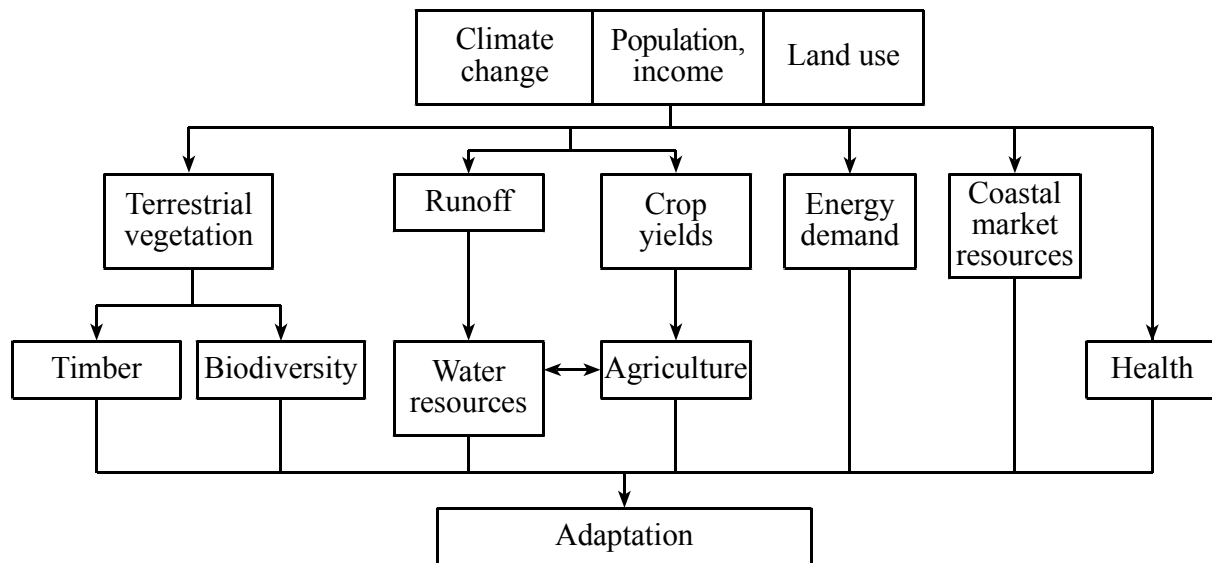


Figure 1. Structure of California climate change implications study

The scenarios were then used in the individual studies displayed in the boxes in the second and third rows of Figure 1 to assess potential impacts of climate change on various sectors of the economy and the natural environment. A number of individual studies fed into other, related studies; for example, estimates of runoff fed into the water resources study, and that study also accounted for changes in demand for irrigation.

The results of the studies can be useful for examining adaptation needs, but no specific study on adaptation was done for this assessment.

Socioeconomic scenarios

California's population, which was approximately 33 million in 1998, is projected to continue increasing substantially in this century. We developed two population scenarios to capture a wide range of potential growth. In the high growth scenario, population reaches 67 million by 2060 and 92 million by 2100; in the low growth scenario, population stabilizes at 67 million by 2060.

We assumed that per capita income will continue increasing, but the degree to which it does so is likely to be affected by the rate of population growth and immigration. We assumed that per capita income would grow 1% per year under the high population-growth scenario – because of more immigration of relatively low wage earners – and 2% per year under the low population-growth scenario.

Based on our assumptions of population and economic growth, Landis and Reilly estimated changes in urbanization patterns ("land use" in Figure S.1) for statewide populations of 45 million (which is projected for 2020), 67 million, and 92 million. Figure 2, Figure 3, Figure 4, and Figure 5 display current urbanization patterns, along with the projections for statewide populations of 45.5 million, 67 million, and 92 million in 2100.

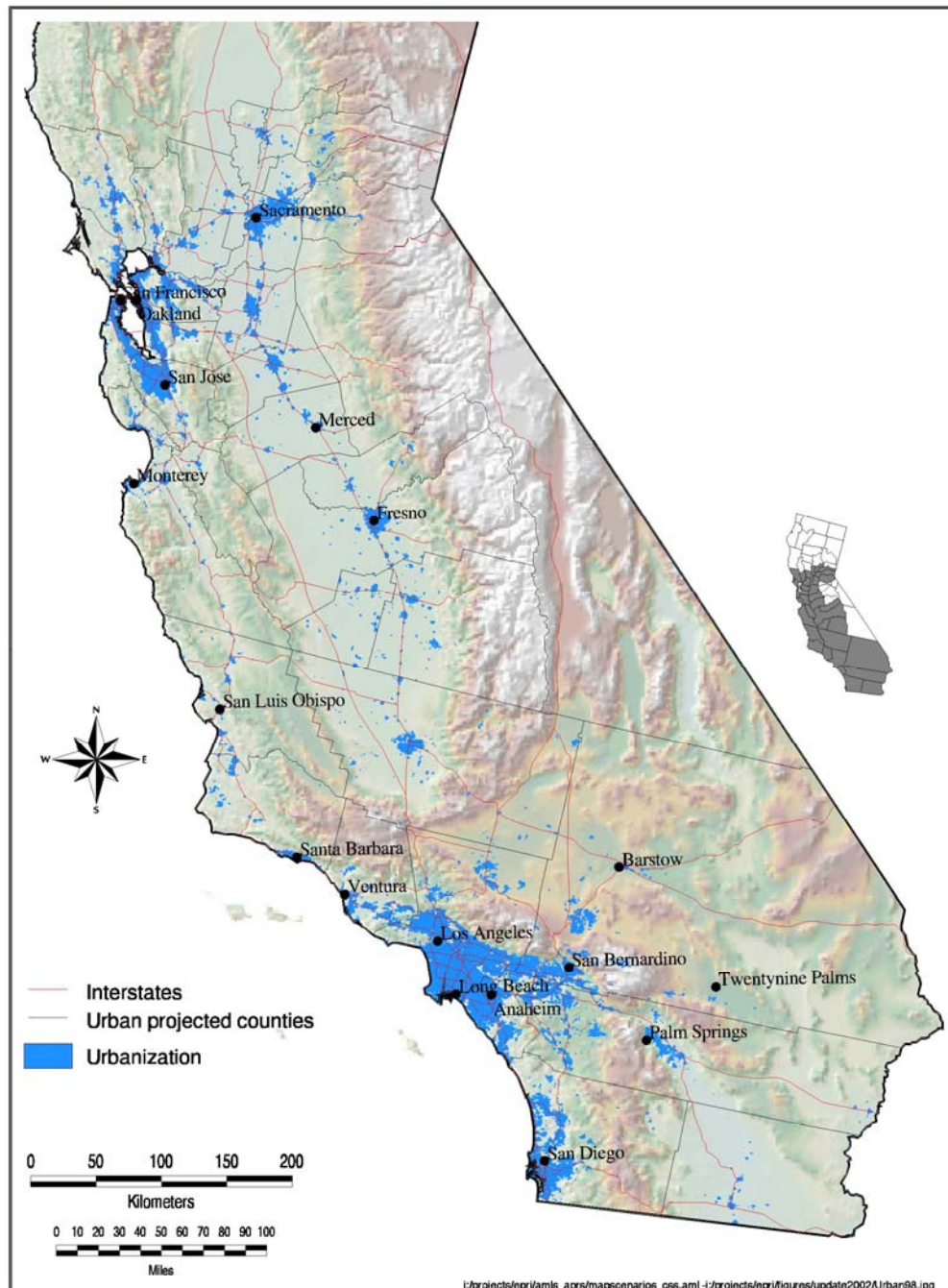


Figure 2. Estimated Distribution Of Urban Areas Under The 33 Million (1998) Scenario

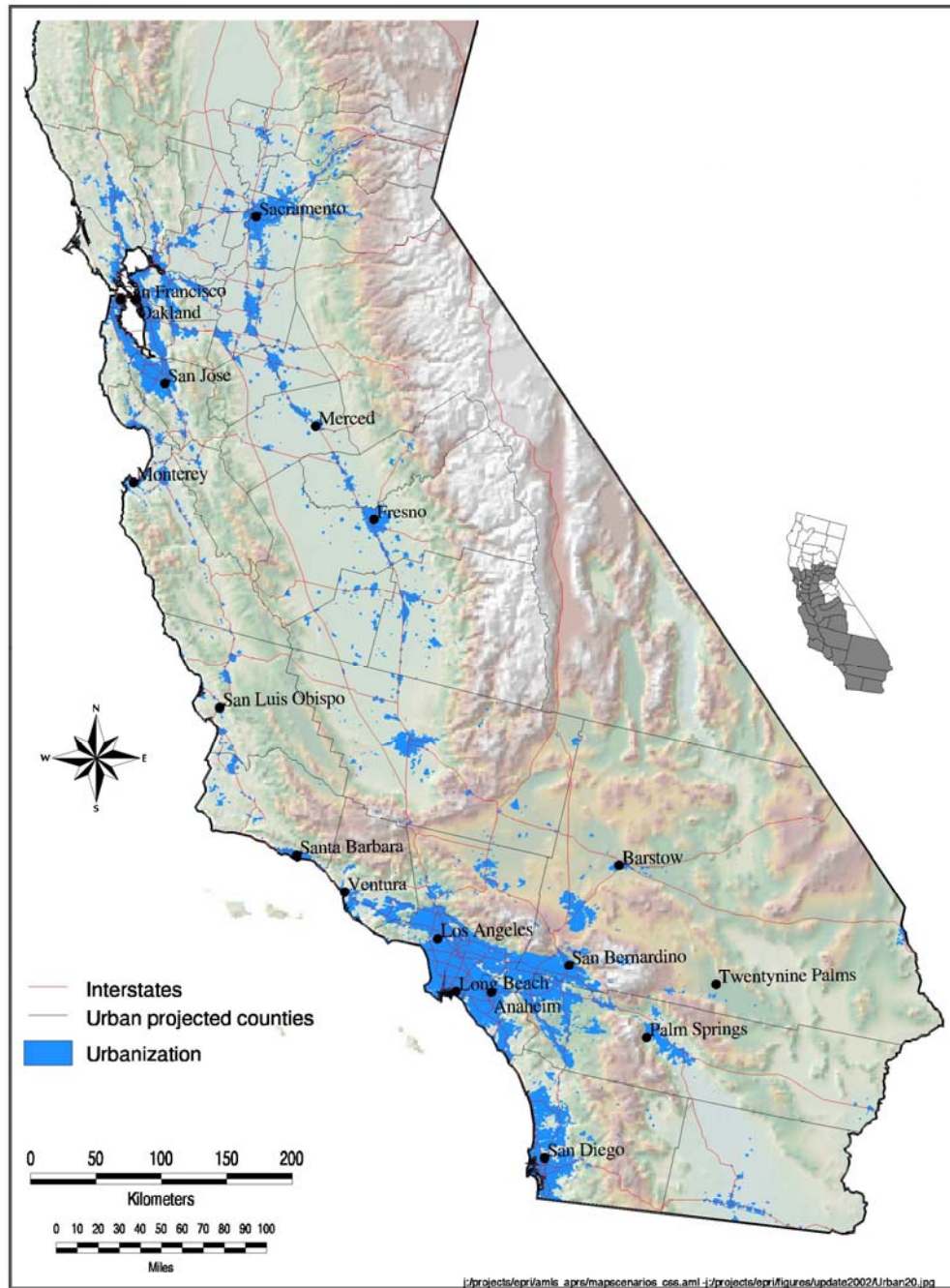


Figure 3. Estimated Distribution Of Urban Areas Under The 45.5 Million Scenario

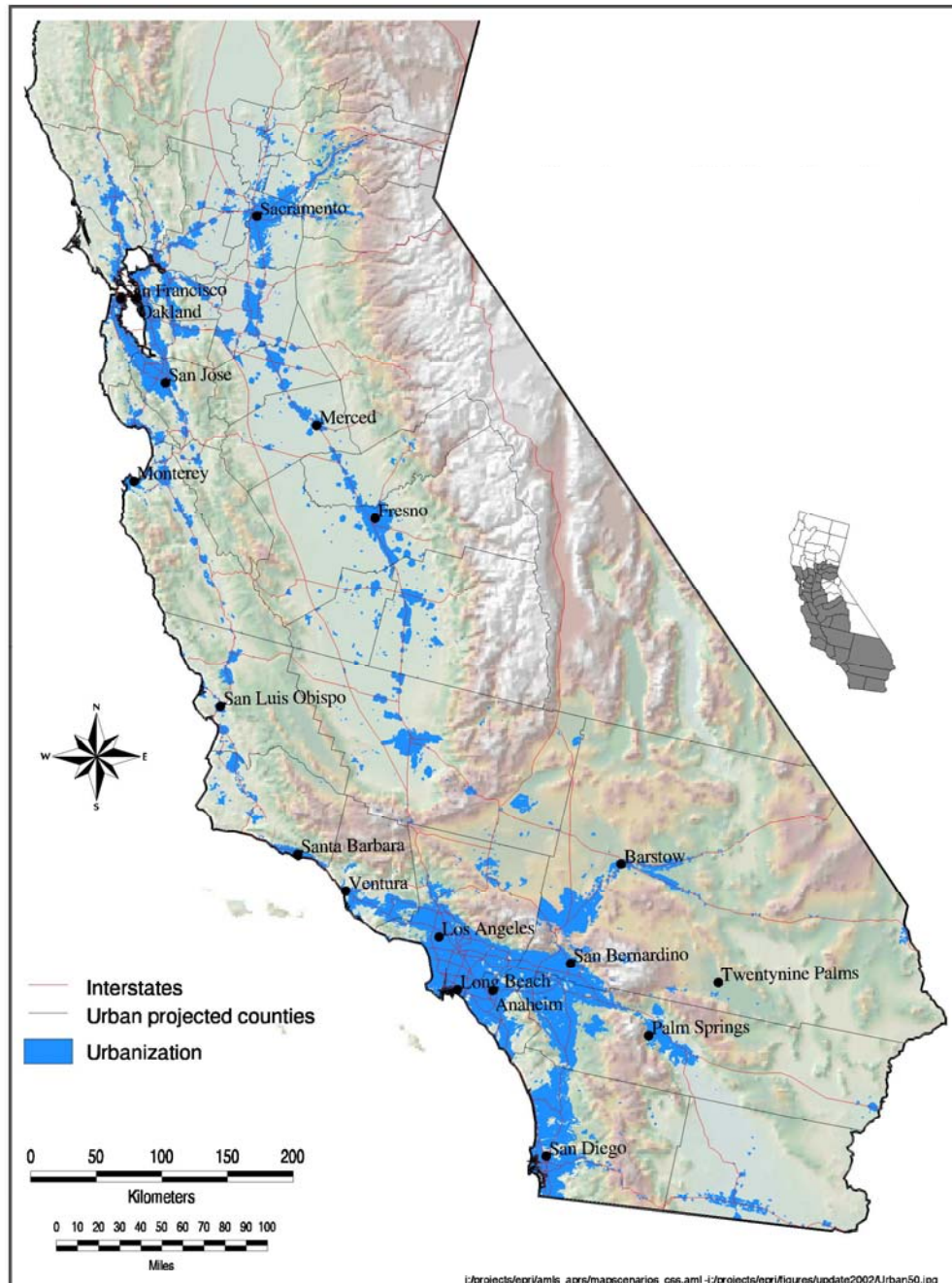


Figure 4. Estimated Distribution Of Urban Areas Under The 67 Million Scenario

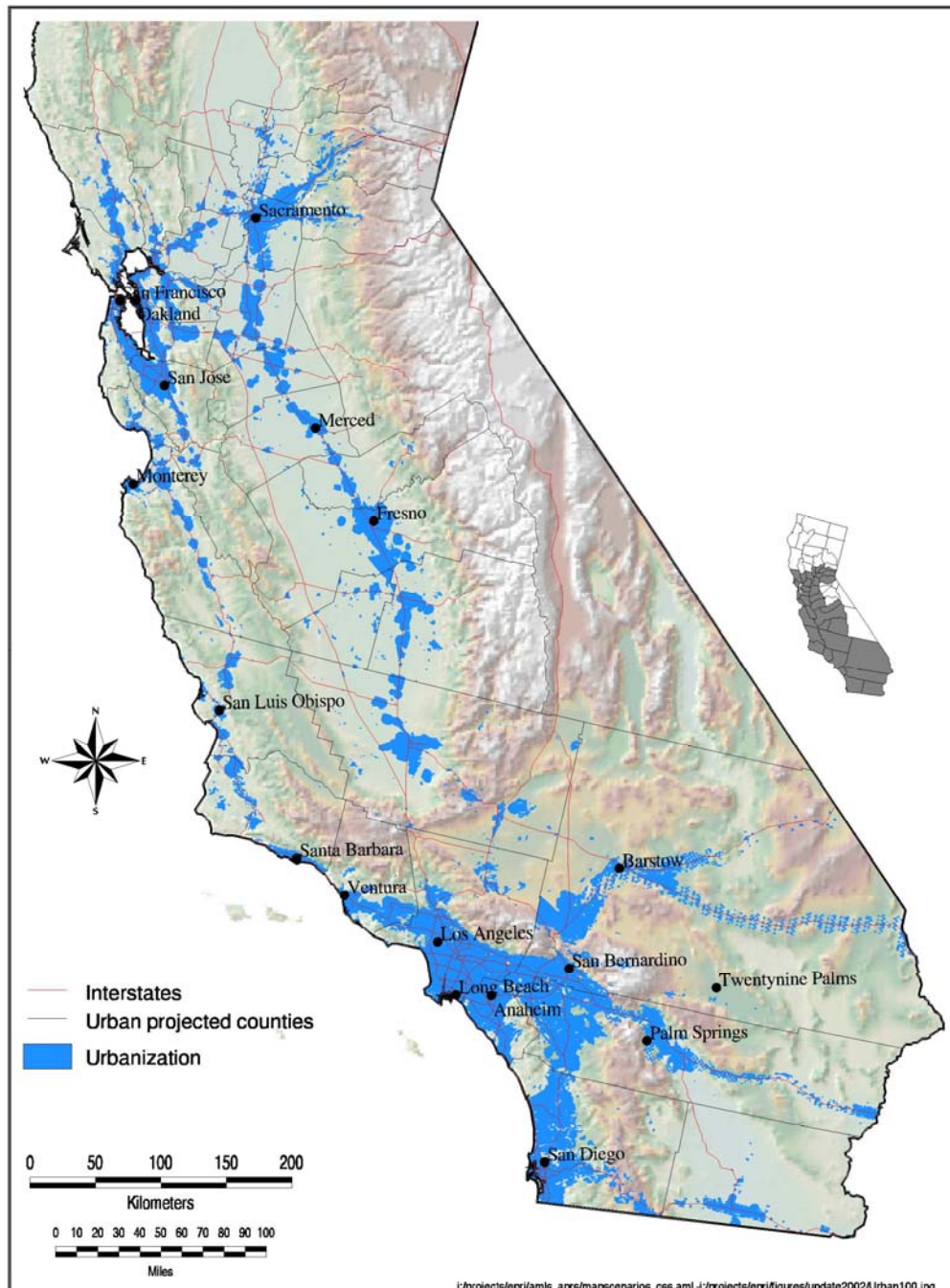


Figure 5. Estimated Distribution Of Urban Areas Under The 92 Million Scenario

Climate change scenarios

A workshop was held with experts in the science of climate change in June 2000, in Sacramento, to discuss what is known about how the state's climate may change. All of the models suggest that California will get significantly warmer over the century. However, there is less agreement

on future precipitation. Most climate models examined at the meeting estimated that California's climate will get wetter, while some show it getting drier. The estimated magnitudes of change in precipitation varied widely across the models. However, the models tend to agree on the seasonal pattern of changes, estimating that winter precipitation will increase and summer precipitation, which is already quite low across the state, will decrease. (More recent analysis of climate models shows that they do not, on average, show California getting wetter or drier. Results vary across models and no firm conclusion about the future change in direction of precipitation can be drawn.)

To represent the range of uncertainty from the reviewed projections, we selected a combination of two general circulation model (GCM) runs and a set of uniform scenarios (which assume uniform changes in the historical climate data for all temporal and geographical scales).

An analysis of temperature and precipitation projections from more than 20 climate models found that the Hadley (HadCM2) scenario, which was also used in the U.S. National Assessment, is one of the wettest models and the Parallel Climate model (PCM) is one of the driest. We deliberately selected these scenarios to represent very wet and very dry conditions. Their outcomes, then, are possible, but not necessarily likely.

The set of incremental scenarios assume a uniform change in temperature and precipitation across the state in all months to capture more potential changes than represented by the two GCM models. Even though we know that changes will vary across the state and by season, uniform incremental scenarios help us better understand the sensitivities of various affected systems to climate change.

The GCM and incremental scenario implications for 2100 temperature and precipitation are displayed in Table 1. All of the scenarios are dynamic, changing over time from our current climate to the climate depicted in Table 1. The GCMs provide this dynamic time path. A steady, linear change from current to future climate is assumed for the uniform scenarios.

Table 1. Climate Change Scenarios For California For 2100

Climate Change Scenarios For California For 2100		
GCM Scenario	Incremental Scenarios	
	Change In Temperature (°C)	Change In Precipitation (%)
GCM		
HadCM2	+3.3	+58
PCM	+2.4	-21
Incremental		
1.5°C, 0% P	+1.5	+0
1.5°C, 9% P	+1.5	+9
3°C, 0% P	+3	+0
3°C, 18% P	+3	+18
5°C, 0% P	+5	+0
5°C, 30% P	+5	+30

A number of important limitations are inherent in such a study of climate change:

- How socioeconomic conditions will change is uncertain. Changes not just in population and wealth, but also in technology can have a substantial effect on the vulnerability of California to climate change. Some of these changes can increase vulnerability, while others can decrease it.
- Climate will change, but how it will do so is uncertain.
- The scenarios do not address potential changes in climate variability or changes in the frequency of extreme events, because there is uncertainty about how these will change. To be sure, variability will not stay the same and such changes could be quite important for California. For example, an increase in storm frequency or intensity could result in more damage.

Project Outcomes

This section summarizes the approach and key outcomes from the individual studies conducted as part of this project. First, we present potential changes in terrestrial vegetation and the implications of these changes for both biodiversity and timber production. We then address potential impacts on water resources and agriculture. Finally, we address potential impacts on energy and coastal resources, and review an initial study of the historical relationship between climate variability and health in California.

1. Terrestrial vegetation

Three studies were conducted to examine how climate change may affect the distribution and productivity of terrestrial ecosystems, biodiversity (of terrestrial vegetation communities), and forestry.

Terrestrial ecosystems

Lenihan et al. used a dynamic general vegetation model (MC1), which estimates both the distribution and the productivity of terrestrial ecosystems such as forests, grasslands, and deserts at a scale of 100 km² (39 square miles), the highest resolution at which a dynamic model has been applied in California.

They estimated that under all climate change scenarios, forests and other types of vegetation will migrate to higher elevations as warmer temperatures make those areas more suitable for survival. For example, with higher temperatures, the area of alpine and subalpine forests will be reduced as evergreen continental forests and shrublands migrate to higher altitudes. They estimated that if it gets wetter, forests would expand in northern California and grasslands would expand in southern California. If it gets drier, areas of grasslands would increase across the state. Both wetter and drier scenarios resulted in increases in carbon storage (biomass) in California vegetation of between 3% and 6%. Wetter conditions generally allow for more biomass. Under drier conditions, grasslands, which store a relatively high amount of carbon below ground, expand.

Lenihan et al. found that the frequency and the size of fires would increase under most scenarios; however, the change is not significant until the latter part of the century. The drier scenarios result in more frequent fires and more area consumed by fires. The wetter scenarios

result in fires of greater intensity than those in the dry scenarios because more fuel (vegetation) would grow when it is wet to be consumed by fire during occasional dry periods.

Biodiversity

Galbraith et al. combined the estimated urbanization patterns (Landis et al.) with the estimates of change in the distribution of terrestrial ecosystems (Lenihan et al.) to examine relative effects of climate change and urbanization on biodiversity.

In addition, urbanization would slightly reduce the diversity of vegetation communities across the state. However, the area covered by different vegetation types would be affected much more by climate change than by urbanization. Galbraith et al. found that a warm and wet climate could result in little change or even an increase in diversity; a warm and dry climate could reduce community diversity much more than would urbanization.

Galbraith et al. also examined potential implications of these two stressors on a threatened and valuable vegetation type along California's coast, coastal sage scrub (CSS). In contrast to the statewide effects, the relative effects of urbanization and climate change may be quite different on the local scale, particular for habitats already strongly affected by urbanization. Development has already reduced CSS by 90%, and additional development during this century could reduce the current CSS habitat by up to another 20%.

The results are displayed in Figure 6 and Figure 7. Figure 6 displays urbanization under the 92 million population scenario in blue. The purple boxes are where CSS is projected to survive if there is no climate change. Figure 7 displays where CSS is consistently projected to survive under all of the climate change scenarios. Each scenario results in some loss of CSS and some relocation. The two purple boxes show CSS remaining and not threatened by development, and the two red boxes show areas that would persist under all climate change scenarios but are threatened by development under the 92 million population scenario.

Under all the climate change scenarios, only a small fraction of CSS would persist, and more than half of these potentially surviving areas would be threatened by development. This preliminary analysis identifies areas that could be the focus on conservation efforts.

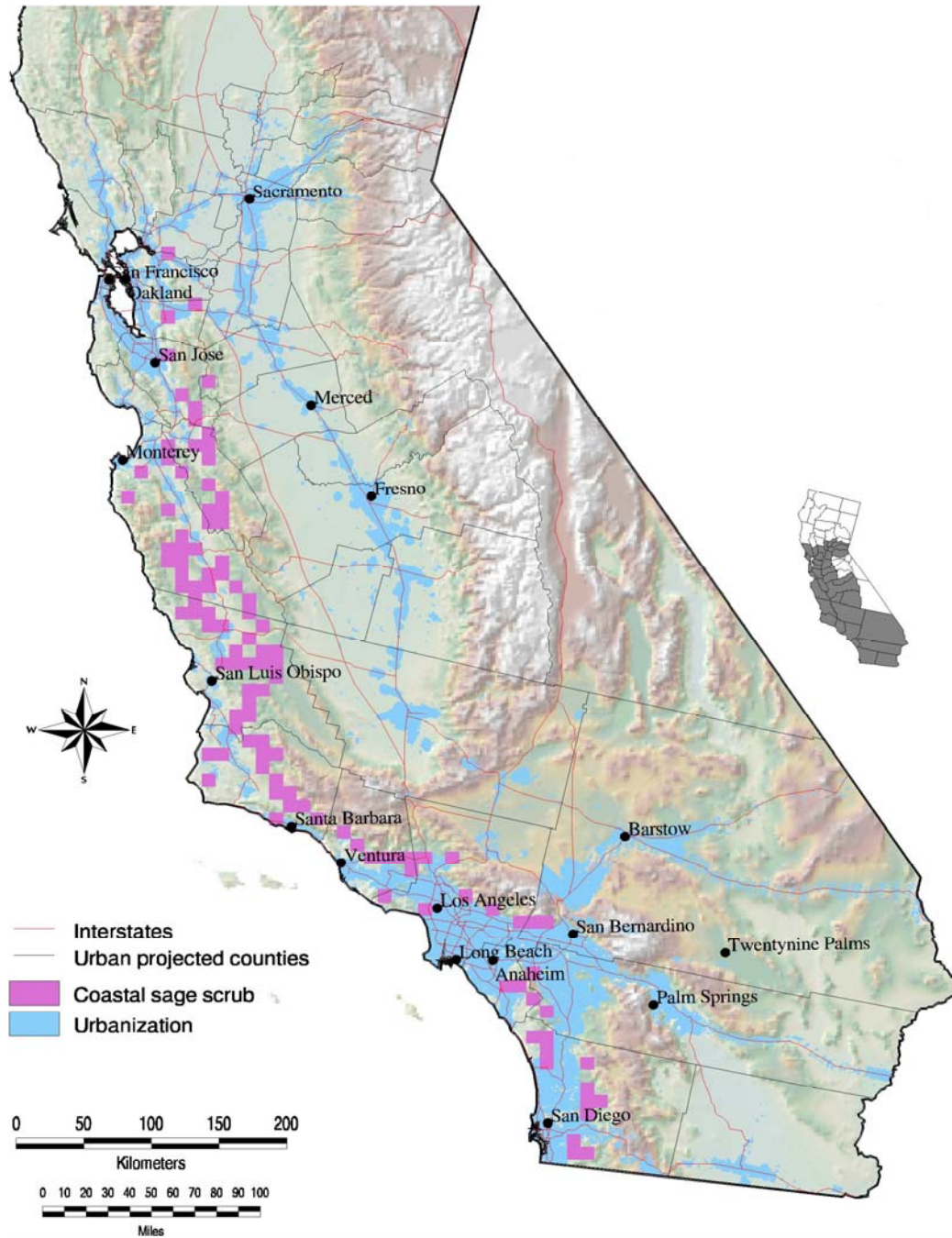


Figure 6. Potential Current Distribution Of CSS Under The 92 Million Population Scenario

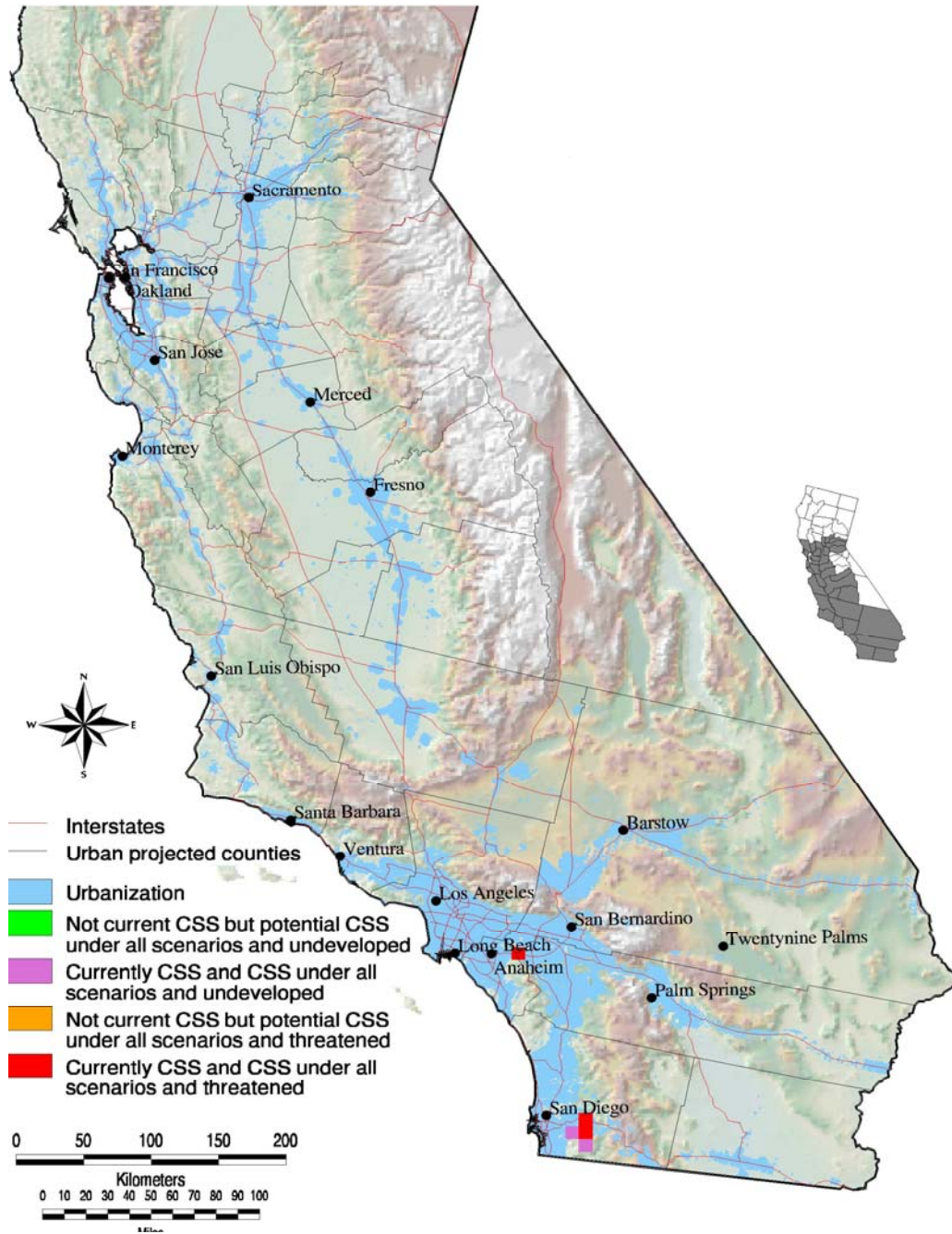


Figure 7. Potential Distribution Of CSS By 2100 Under All Climate Change Scenarios And A 92 Million Population Scenario

Timber

Mendelsohn combined the estimated changes in location and productivity of California vegetation with a timber production model to assess the potential impacts of climate change on timber production. This study focused on softwoods on privately owned lands, assuming that little timber on public lands would be harvested.

Mendelsohn found that areas that can support growth of commercial species (mainly softwoods) could expand in northern California. But in most of California, the area that could support growth of commercial timber species could contract, especially toward the end of the century. However, increased CO₂ concentrations in the atmosphere could help forests grow faster, particularly under warmer and wetter conditions. The net result of these changes would be an increase in supply of California-grown timber throughout the next several decades but a possible decline closer to the end of the century.

2. Water resources and agriculture

Runoff

Miller et al. estimated changes in snowpack, snowmelt, and runoff in six key basins: the Smith River, Sacramento River, Feather River, American River, Merced River, and Kings River. They found that higher temperatures are likely to have a substantial effect on snowpack, snowmelt, and runoff. Snowpacks will begin to melt earlier in the year, resulting in earlier and higher peak flows, which in turn could result in increased flooding. However, even under scenarios with reduced precipitation, such as PCM, peak flows were estimated to increase, because of earlier melting of the snowpack. Those peak flows would increase substantially under the wet scenarios. Changes in total annual runoff depends on the assumed changes in precipitation.

Water Resources

Water resources and supply are likely to be substantially affected by population growth and climate change. Lund et al. estimated that population and economic growth alone could increase urban use of water by two-thirds, thereby reducing water use by agriculture in California by about 10%. Using calculations of changed runoff in specific basins by Miller et al., Lund calculated statewide changes in runoff. The PCM scenario results in up to a 26% reduction in runoff from the mountains; the HadCM2 scenario results in increases of as much as 77%. The incremental scenarios lie between these outcomes, ranging from virtually no change to increases up to 28%. The effects of sea level rise were not considered in this analysis.

The combined results of estimated changes in runoff from snowpack, surface water, groundwater inflow, and reservoir evaporation on total raw water availability (not allocations) are displayed in Table 2. Changes range from a 12% increase under HadCM2¹ to a 25% decrease under PCM. The incremental scenarios result in either little change or in reductions.

¹ The large increase in precipitation under HadCM2 translates into a much smaller increase in raw water availability because much of the increase is assumed to happen in winter when reservoirs are too full to capture it. Thus, most of the increase is spilled and goes out to sea. The study did not examine increasing storage potential.

Table 2. Raw Water Availability Estimates And Changes

Raw Water Availability Estimates and Changes (Without Operational Adaptation, In MAF/Yr)		
Climate Scenario	Average Annual Water Availability	
	Volume (MAF)	Change From Historical (MAF, %)
(1) 1.5°C, 0% P	35.7	-2.1 (-5.5)
(2) 1.5°C, 9% P	37.7	-0.1 (-0.4)
(3) 3.0°C, 0% P	33.7	-4.1 (-10.9)
(4) 3.0°C, 18% P	37.1	-0.8 (-2.0)
(5) 5.0°C, 0% P	31.6	-6.2 (-16.5)
(6) 5.0°C, 30% P	36.2	-1.6 (-4.3)
(7) HCM 2010-2039	41.9	4.1 (10.8)
(8) HCM 2050-2079	40.5	2.7 (7.2)
(9) HCM 2080-2099	42.4	4.6 (12.1)
(10) PCM 2010-2039	35.7	-2.1 (-5.6)
(11) PCM 2050-2079	32.9	-4.9 (-13.0)
(12) PCM 2080-2099	28.5	-9.4 (-24.8)
Historical (1922-1993)	37.8	0.0 (0.0)

Changes in deliveries to urban and agriculture users are displayed in Figure 8. In the analysis, higher value users are assumed to get deliveries before lower value users. Deliveries to agriculture are affected much more by climate change than are deliveries to urban users because, on the margin, agriculture has lower values than urban uses. Under HadCM2, both urban and agriculture would get slightly more water than with no climate change. Under the PCM scenario, urban deliveries would be reduced by 100,000 acre feet per year, less than 1% of what they are estimated to use without climate change, while agriculture would be reduced by 8.8 million acre feet, about 35% of the amount used without climate change.

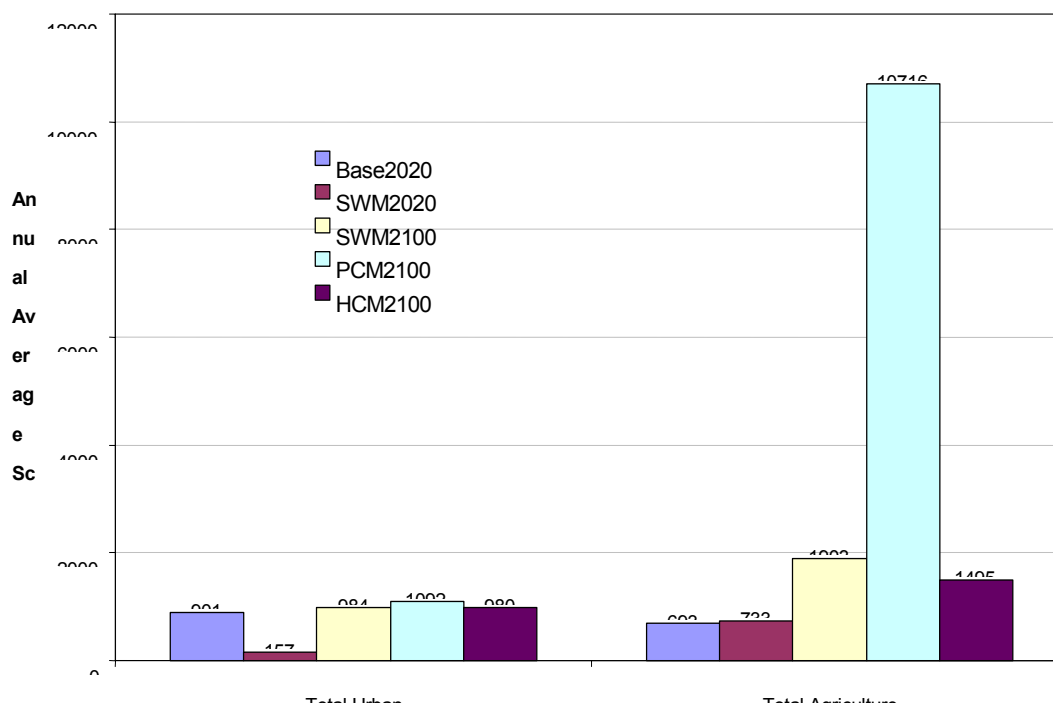


Figure 8. Total Volumetric Scarcity

Deliveries to southern California are estimated to be relatively unaffected by climate change because the region becomes more urban and continues to use its capacity from the Colorado and California Aqueducts. Deliveries to other regions of California would be reduced under the PCM scenario. In addition, population growth results in less flow for critical environmental needs in many rivers, lakes, and refuges. The effect of the dry PCM scenario is much more severe than future population growth, while the wet HadCM2 scenario can result in higher flows that in some cases, offset the higher demands from future population growth.

The environmental impacts of changes in runoff and water supply largely depend on whether runoff increases or decreases. While in the HadCM2 scenario runoff would increase (which could cause adverse environmental problems such as increased sediment and nutrient loadings in water bodies), the decreases under the PCM scenario would be so large that there would not be enough runoff in the Trinity and Sacramento Rivers and in the Mono Lake inflow to meet current environmental needs

Under the dry PCM scenario, hydropower revenues would be reduced by 30%, while under the wet HadCM2, they would increase by more than 50%. Even under HadCM2, generation would increase in the winter, but could decrease in the summer. The reduction in summer hydropower generation would come as summer demand for energy for cooling increased (see below).

Crop Yields And Irrigation Demand

With California's wide diversity of crops, modeling the effects of climate change on crop yields is challenging. Physical process models exist for only a few of the crops grown in the state. To fill this gap, Adams et al. used statistical methods to estimate how the yield of a wide variety of California crops could be changed. They regressed county-level crop yields on monthly

growing season temperature and precipitation in California to develop statistical relationships between climate and yield. They also estimated potential carbon fertilization effects (higher CO₂ levels increase plant growth and reduce water needs in some species) and considered the effect of different soil types.

Adams et al. estimated that the combination of higher temperatures and CO₂ fertilization tends to result in increased crop yields in the relatively cooler northern and coastal regions and decreased crop yields in the relatively warmer San Joaquin and desert areas. There is substantial variation in yield changes among different types of crops. They estimated that demand for irrigation water would rise by a few percentage points. In addition, Adams et al. found that technology improvements could substantially increase yields, as they have since World War II. However, although we expect technology to continue to result in yield improvements, the magnitude is uncertain.

The information on changes in crop yield and water needs was used by Howitt and Tauber in an economic model for agriculture, the Statewide Water Agricultural Production (SWAP) model. This economic optimization model identifies demand for water (input) for each region, along with the resulting value of agricultural output. SWAP's objective is to maximize each region's total net returns from agricultural production subject to pertinent production and resource constraints on water and land.

Factoring in increases in population (as estimated by Landis and Reilly), Howitt and Tauber estimated that from 2020 to 2100 land in agriculture will drop by 700,000 acres, or about 10%. Some regions, such as San Diego County, would see agricultural land reduced by more than one-half. They also found that by 2100 demand in those regions for irrigation would increase by 7 to 20% in the incremental scenario of +3°C and 18% increase in precipitation and by 15 to 30% in the HadCM2 scenario.

The effects of the potential changes in water supply on statewide agricultural production are relatively small, although some counties could be more severely affected. The wet HadCM2 scenario results in virtually no change in statewide production. The approximate one-quarter decrease in water supplies for agriculture under the PCM scenario results in a 6% decrease in agricultural income, or about \$1 billion. The reason that the percentage change in income is so much smaller than the percentage change in water deliveries is because the reductions in crop acreage are concentrated mainly in low-value and high-water-using crops such as alfalfa. But, these changes do not happen equally across the state. The model projects that some regions would receive slightly more water even under PCM, while others would have reductions in deliveries of about three-fourths and reductions in income of one-third to one-half. The study found that Palo Verde and some counties in the Sacramento Valley could have the largest reductions in irrigation water deliveries and, hence, production.

3. Other studies

We also explored potential impacts on energy demand, coastal resources, and human health. The health analysis is a historical analysis based on examination of recent El Niño and La Niña events rather than an effort to project possible future effects.

Energy

Using cross-sectional analysis (which compares behavior in different climates), Mendelsohn estimated the response to climate change of energy use for space heating and cooling in

residences and businesses across California. Not surprisingly, energy demand is projected to increase most in the southeastern desert areas. The northern maritime and high alpine counties have the smallest projected changes in energy expenditures.

Higher temperatures are estimated to increase statewide energy demand and expenditures. Mendelsohn estimated that by 2100 residential energy expenditures could increase from \$1.6 billion (a 4% increase) to \$10.2 billion (a 17% increase) because of climate change (Table 3). Increased use of energy for cooling more than offsets reduced use of energy for heating. The higher costs account for installing and using more air conditioning as an adaptation to climate change. Mendelsohn estimated that annual energy expenditures for the commercial sector would increase by about \$300 million (a 2% increase) to almost \$9 billion (a 36% increase), depending on the amount of increase in temperature (higher temperatures result in greater expenditures) and whether buildings are assumed to be unchanged or to be modified in response to climate change. Total energy expenditures could increase 0.5% to 6% by 2020 and up to 9% by 2060. By 2100, total energy expenditures for the state are estimated to rise from \$1.9 billion to \$3.5 billion (a 4% increase) for a 1.5°C warming and from \$9.4 billion to \$18.9 (a 18 to 22% increase)² billion for a 5°C warming. Increased expenditures are 10% to 24% higher when long-term adjustments are taken into account.

2. The increases are measured off different baselines using different assumptions about the growth in energy demand without climate change.

Table 3. Increase In Annual California Commercial, Residential, And Total Energy Expenditures By 2100 (\$ Million)

Increase In Annual California Commercial, Residential, And Total Energy Expenditures By 2100 (\$ Million)						
Scenario	Residential		Commercial		Total	
	Short-run	Long-run	Short-run	Long-run	Short-run	Long-run
1.5°C, 0% P						
Slow	1,609	1,596	333	503	1,942	2,099
Fast	2,154	2,293	599	906	2,753	3,199
1.5°C, 9% P						
Slow	1,764	1,794	333	503	2,097	2,297
Fast	2,411	2,622	599	906	3,010	3,528
3.0°C, 0% P						
Slow	3,158	3,820	1,370	1,791	4,528	5,611
Fast	4,306	4,854	2,468	3,226	6,774	8,080
3.0°C, 18% P						
Slow	3,462	3,712	1,370	1,791	4,832	5,503
Fast	4,807	5,501	2,468	3,226	7,275	8,727
5.0°C, 0% P						
Slow	5,440	6,054	3,939	4,850	9,379	10,904
Fast	7,735	9,125	7,095	8,736	14,830	17,861
5.0°C, 30% P						
Slow	5,934	6,700	3,939	4,850	9,873	11,550
Fast	8,545	10,187	7,095	8,736	15,640	18,923
HadCM2 2100						
Slow	4,219	4,740	1,973	2,522	6,192	7,262
Fast	5,915	7,099	3,553	4,543	9,468	11,642
PCM 2100						
Slow	3,067	2,947	1,172	1,534	4,239	4,481
Fast	4,010	4,126	2,111	2,763	6,121	6,889

Coastal Market Resources

Neumann et al. estimated the cost of protecting low-lying developed coastal areas plus the value of land that is allowed to be inundated. Although most of California's coast is cliffs, substantial portions are low-lying and highly developed. They examined scenarios where sea level rises linearly to 33 cm, 50 cm, 67 cm, and 100 cm by 2100, capturing a wide range of potential changes. They examined selected sites along the California coast to determine what impact rising seas might have on the state.

Neumann et al. examined decisions on protection versus abandonment of coastal property at each site based on a benefit-cost analysis of which approach is most efficient. Other factors may intervene to affect actual decisions on whether to protect or abandon coastal areas. In addition to this economic analysis, they conducted a sensitivity analysis that assumed the entire area between Los Angeles and San Clemente will be protected by beach nourishment and armoring.

Neumann et al. found most of the low-lying and exposed urban coastline has sufficiently high value to justify protection by sea walls. The undiscounted cost of protecting vulnerable areas over the next 100 years is estimated to be approximately \$700 million for a 50 cm sea level rise and \$4.7 billion for a 1 m sea level rise. The discounted value is estimated to be between \$46 and \$123 million for a 50 cm sea level rise and \$198 and \$635 million for a 1 m sea level rise, reflecting the result that most of the costs are incurred midcentury or later. Annual costs for a 50 cm sea level rise by 2100 are estimated to range from \$8 million to \$15 million. Annual costs for a 1 m sea level rise are estimated to range from \$40 million to \$100 million.

The study did not estimate wetland loss as a result of sea level rise, or the additional loss of wetlands resulting from building coastal defense measures. In places such as San Francisco Bay, the combination of sea level rise and coastal defense measures can result in a substantial reduction in wetlands and tidal flats.

Human health

Climate change is expected to affect the intensity and frequency of the El Niño/Southern Oscillation, although the exact nature of the changes is uncertain. This study examined how health in California was affected by recent El Niño/Southern Oscillation events.

Ebi and Kelsh analyzed the effect of recent El Niño events on hospital admissions in Los Angeles, San Francisco, and Sacramento for pneumonia or heart conditions. They found that results varied considerably based on geography. Hospitalizations for viral pneumonia in the San Francisco and Los Angeles areas increased significantly with a decrease in minimum temperature. Sacramento area hospitalizations increased significantly with a decrease in maximum temperature and an increase in minimum temperature. For cardiovascular diseases and stroke, changes in both maximum and minimum temperature were associated with significant increases in hospitalizations in San Francisco for all types of cardiovascular disease for men and women 70 years of age and older. Ebi and Kelsh found the strongest association between temperature change and hospitalizations in San Francisco, possibly because fewer residences in San Francisco are consistently temperature controlled.

Conclusions

On the whole, the results presented here suggest that the impacts of climate change on California are complex, defying simple description. Whether California loses or benefits on the whole is partly a matter of how climate changes, but also a matter of how impacts are valued and even how prices for globally traded products — such as those of agriculture and timber — change.

On the negative side, there could be increases in floods or droughts; increased energy costs; decreased water deliveries, particularly to agriculture and instream uses such as aquatic ecology and hydropower; damages to the coastline and increased costs for protecting coastal resources; loss of biodiversity (at least measured at the ecosystem level); and long-run declines

in timber production. On the positive side, crop yields could increase overall and timber supply could increase in the short run; both would benefit consumers.

The study also found a substantial potential for managed systems such as water resources and agriculture to shift decreases in water supply to low value uses so as to reduce total economic impacts. There would still be net losses but the magnitude would be significantly lower than if such adaptations were not made. Whether such adaptations would be realized is difficult to determine, but the study demonstrates that the potential for adaptation to ameliorate many of the adverse impacts of climate change on societal systems is quite high.

Regions differ in how they could be affected by climate change. Southern California faces relatively larger increases in energy costs, greater decreases or lesser increases in crop yields, and a substantial share of the costs of sea level rise (although San Francisco Bay would also have a substantial portion of sea level rise adaptation costs). However, parts of the Sacramento Valley may be vulnerable to reductions in water supply for irrigation, and the Sacramento region is at particular risk from increased flooding. In addition, northern California timber producers are at risk if climate change reduces global timber prices.

Some of the most important impacts on the state depend on how climate change affects the rest of the world. The prices in agriculture and timber depend on how climate change affects the global supply of food and wood products. If climate change has a positive effect on supply, prices will drop, negatively affecting California producers but giving California consumers a large gain. On net, global price declines will be a benefit for California because the consumer gains will outweigh the producer losses.

Table 4 presents partial economic results from these studies. We did not attempt to assign an economic value to potential ecosystem or health changes. The studies suggest that there could be net damages to California's economy, with impacts ranging from hundreds of millions to billions of dollars in the early part of this century and billions to tens of billions of dollars in the latter part of this century. The largest economic impacts are consistently in energy. In the very dry PCM scenario, agriculture has relatively large impacts, although still smaller than energy.

Table 4. Summary Data, Annual Benefits – 2100 (\$Millions)

Summary Data, Annual Benefits — 2100 (\$Millions)								
Scenario/ Study	Hadcm2	PCM	+1.5°C 0% P	+1.5°C +9% P	+3°C 0% P	+3°C +18% P	+5°C 0% P	+5°C +30% P
Urban Water Use	3	-87						
Operating Costs Water System	237	-147						
Agriculture	15	-1,113						
Timber	76 To -140	86 To -132			-124 To -390	-93 To -266	-159 To -315	-86 To -261
Energy (Assuming Price Increase)	- 6,19 2 To - 11,6 42	- 4,2 39 To - 6,8 89	- 1,9 42 To - 3,1 19	- 2,0 97 To - 3,5 28	- 4,5 28 To - 8,0 80	- 4, 8 3 To 2 - T o - 8, 7 2 7	- 9,3 79 To - 17, 86 1	- 9,8 73 To - 18, 92 3
Coastal (Sea Level Rise Scenarios)				-2 To -6 (0.33 M)	-8 To -15 (0.5 M)	-12 To -30 (0.67 M)	-39 To -104 (1 M)	
Note: Positive numbers are benefits and negative numbers are damages.								

Readers should bear in mind that there are limitations in any modeling study. Simplifying assumptions are made in all models. We examined a limited set of scenarios about future conditions without climate change. Some of the scenarios capture very dry or wet conditions, to give a sense of what may happen, but they may not reflect what will actually occur. We also made assumptions about how systems would respond to climate change, but these predictions are also uncertain. Some assumptions, such as assuming perfect information and completely free markets in some sectors, tend to make results more positive than we expect them to be. Other assumptions, such as not fully accounting for technological improvements or accounting for all adaptations, result in more pessimistic outcomes than we might expect. In the report, we have tried to make these assumptions clear. We advise readers to look for important insights that can be learned about the sensitivity and potential response of systems to climate change and not interpret results as certain outcomes. While these studies cannot predict the precise effects of climate change, they provide insight into how California may be affected by climate change and the relative sensitivities of its sectors.

Additional research is needed because despite the substantial advances that have been made toward understanding the impacts of climate change, there remain large uncertainties about the impacts of warming. Among the potential topics are analysis of implications of rapid climate change or change in variability, improved understanding of impacts on natural ecosystems and human health, and analysis of adaptation options.

1.0 Introduction

This report presents the results from a set of coordinated, in-depth analyses of the potential effects of climate change on California. The work was initiated and primarily funded through the California Energy Commission's (Commission) Public Interest Energy Research (PIER) program. The Electric Power Research Institute (EPRI) provided significant cofunding and assisted in research management.

These studies were designed to help natural resource managers and other policy makers in California better understand the potential effects of climate change on the state. This focus complements earlier Commission publications (California Energy Commission, 1991 and 1998) that were focused more on California's energy sector and policies and on measures to reduce the greenhouse gas emissions implicated in climate change. This report does not address the possible implications of climate policies for the energy, agriculture, or other sectors of California's economy, but focuses its inquiry on the possible implications of a changing climate.

The studies explore a broad range of possible changes in climate that could take place in California during the 21st century. Over the century, the population and economy of the state will undoubtedly also change, so the studies examine future climate scenarios against a backdrop of a wide range of socioeconomic scenarios. The studies reveal the possible sensitivity of key sectors of the economy to climate change and explore some of the implications climate change may have for natural resources. The ultimate goal of the studies is to identify key sensitivities of California's natural and economic systems to climate change, providing information that natural resource policy makers can use in developing adaptive policies.

This study is the most integrated and detailed quantitative assessment of the potential impacts of climate change on California conducted to date. Even with such detail and methodological advances, many potential impacts or interrelationships among potential impacts were not examined, and simplifying assumptions are made about baseline conditions and relationships between sectors and climate. As such, this effort should be viewed as a step forward in our understanding of potential climate change impacts on California rather than a final assessment. Results presented should be considered both for the insights they provide about the sensitivity of certain sectors in California to climate change and for the additional questions they identify or refine that may guide future research.

The research described in this report builds on a number of multisector assessments of potential impacts of climate change on California, including those produced by:

- U.S. Environmental Protection Agency (EPA; Smith and Tirpak, 1989). This study was the first wide-ranging assessment of the impacts of climate change on the United States. Organized by the EPA, it explicitly examined potential impacts of climate change on several regions in detail, including California. The study examined impacts on water resources, agriculture, coastal resources, and natural ecosystems and on San Francisco's air quality.
- U.S. Department of Energy (DOE; Knox and Scheuring, 1991). This study, organized by DOE's Office of Environmental Policy Analysis, the Office of the President of the University of California, the Save the Earth Foundation, and the University-wide Energy Research Group, presented a series of papers on the effects of a projected global warming scenario on elements of California's economy, including its water resources,

energy supply and demand, agriculture, forests, terrestrial and aquatic ecosystems, coastal zone, and urban areas.

- The U.S. National Assessment Synthesis Team (NAST, 2000; Smith et al., 2001; Wilkinson, forthcoming). Commonly called the U.S. National Assessment, this report was national in scope, but was based on a series of regional assessments. For example, the authors of the California section had extensive consultations with stakeholders and provided new analyses of agriculture, water resources, and ecosystem impacts.

In addition to these multisector assessments of impacts, numerous studies have examined the impacts of climate change on specific sectors in California. Among the more prominent are those by:

- The Union of Concerned Scientists and the Ecological Society of America (Field et al., 1999). This study reviewed the literature on climate change impacts and used expert judgment to identify potential consequences of climate change for societal and natural systems in California.
- Scripps Institution of Oceanography (Barnett et al., in review). This study examined the effect of change in population and runoff on California's water supplies. It used one climate scenario, the National Center for Atmospheric Research's (NCAR) Parallel Climate Model (PCM; Dai et al., 2001), which is one of the climate models used in our study.

The next section describes the project approach, including an overview of the methods we used and a discussion of the limitations inherent in such a study. After that, we present project outcomes in a section that includes key results from each of the project studies. Finally, we offer our conclusions and recommendations. The appendices to this report (I-XV) describe the methods and detailed results for each study.³

2.0 Project Approach

The analytical methods and approaches used to develop this report build on two U.S. assessments (Mendelsohn and Neumann, 1999; Mendelsohn, 2001) that examined the potential impacts of climate change on agriculture, timber, water resources, coastal structures, and energy demand at national and regional levels. Mendelsohn and Neumann (1999) also explored effects on recreation and commercial fishing at the national level. The approaches used here to address timber, coastal structures, and energy demand are direct extensions of those earlier approaches. We used new methods to develop future socioeconomic scenarios; to address ecosystem effects (which were not addressed in the earlier works outside the timber context), particularly in the context of socioeconomic change; and to understand the complex interrelationships between California water resources and agriculture. The individual sector studies are linked by common assumptions about future climate and socioeconomic scenarios and as much as possible by consistent assumptions about future land use.

Teams of researchers from broadly diverse disciplines conducted the individual sector studies, listed in Table 5.

3. PIER Contract 500-97-043 funded this study and EPRI's collaborative program. Appendix XVI provides an overview of the research results developed through this collaborative effort.

Table 5. Research Team

Topic	Researchers	Appendix
Climate Scenarios	Chuck Hakkarinen, EPRI Joel Smith, Stratus Consulting	I
Population and Income Scenarios	Robert Mendelsohn, Yale University Joel Smith, Stratus Consulting	II
Land Use Scenarios	John Landis and Michael Reilly, University of California, Berkeley	III
Ecosystem Effects	James Lenihan, Raymond Drapek, and Ron Neilson, USDA Forest Service, Corvallis, OR Dominique Bachelet, Oregon State University	IV
Terrestrial Vegetation and Land Use Effects	Hector Galbraith, Galbraith Environmental Services Joel Smith and Russell Jones, Stratus Consulting	V and VI
Water Resources	Jay Lund, Marion Jenkins, Tingju Zhu, and Stacy Tanaka, University of California, Davis	VII
Water Runoff	Norman Miller and Kathy E. Bashford, Lawrence Berkeley National Laboratory Erin Strem, NOAA NWS, Sacramento, CA	VIII
Crop Yields and Water Needs	Richard Adams, Junjie Wu, and Laurie Houston, Oregon State University	IX
Agriculture	Richard Howitt and Melanie Tauber, University of California, Davis	X
Energy	Robert Mendelsohn, Yale University	XI
Timber	Robert Mendelsohn, Yale University	XII
Coastal Market Resources	James Neumann, Daniel Hudgens, Jane Leber Herr, and Jennifer Kassakian, Industrial Economics, Inc.	XIII
Human Health (Retrospective)	Kristie Ebi, EPRI Michael Kelsh, Exponent	XIV
Review of Ecosystem Study	Lou Pitelka, University of Maryland	XV

Scenarios for changes in climate (see Appendix I) and in socioeconomic conditions (see Appendices II and III) out to 2100 for California were developed. Using these estimated changes in socioeconomic conditions and climate, the study examined the potential impacts of climate change in three groupings (see Figure 9):

- **Terrestrial Vegetation.** A study of the potential changes in location and productivity of terrestrial vegetation (see Appendix IV) is combined with projections of future land use to explore the combined effect on ecosystems and biodiversity (see Appendices V and

VI). Results from the ecosystem analysis are also combined with a timber market model to examine changes in timber production (see Appendix XII).

- **Water Resources And Agriculture.** Changes in water runoff (see Appendix VIII) and crop yields and water use (see Appendix IX) are estimated for the climate change scenarios. These results are combined with the socioeconomic scenarios to examine changes in demand for and allocation of the state's water resources, as well as changes in crop location and production. Appendices VII and X supply the details on these analyses.
- **Coasts, Energy, And Health.** The first two of these studies examine the combined effects of climate change, population expansion, and economic growth on energy demand (see Appendix XI) and coastal market resources (see Appendix XIII). A final study (Appendix XIV) examines the historical relationship between climate variability and hospitalizations in California. Unlike the other sector studies, the health study is retrospective and does not make any projections about future conditions.

A key element of these studies is that they make more explicit the potential role of adaptation in coping with negative effects of climate change or in taking advantage of any positive impacts. To fully assess vulnerability, it is important to understand not only the biophysical effects of climate change (e.g., how crop yields or water supplies may be affected) but also the degree to which society and nature can respond to these changes. Once these responses have been taken into account, the degree to which systems or regions may be vulnerable to climate change can be determined. These studies make varying assumptions about the ability and willingness of the individual sectors to adapt to climate change. In addition to examining cases that assume that fully informed, rational decision makers are seeking to maximize economic efficiency, some of the analyses also explore cases of more limited adaptation to climate change. Because we do not know exactly how well people will adapt to climate change, we use these assumptions about adaptation to better understand the *potential* for adaptation.

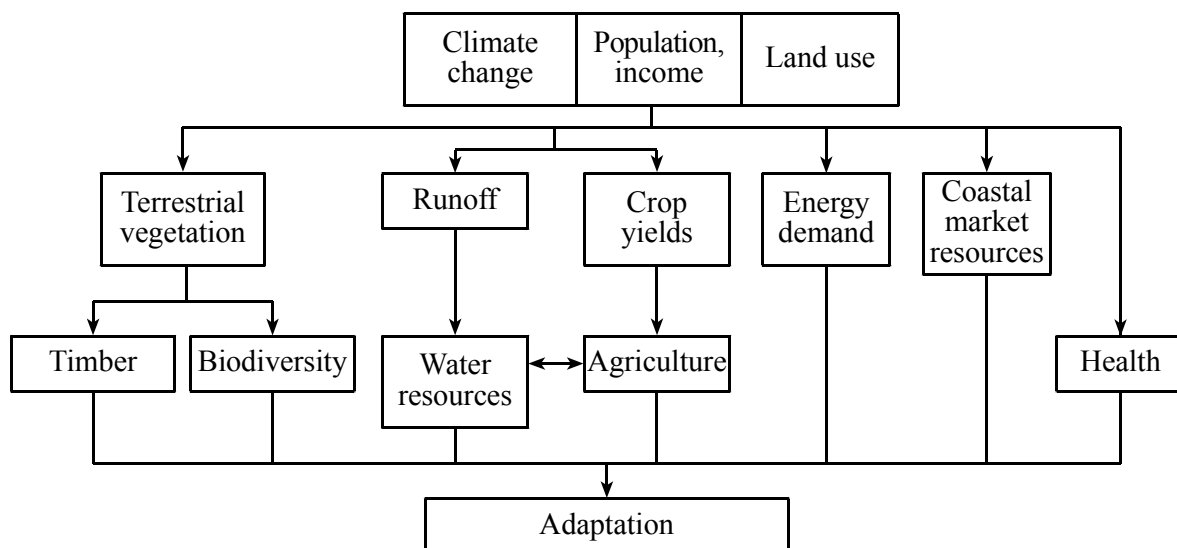


Figure 9. California Climate Change Implications Study

After briefly describing the major limitations to the project, we describe the scenarios of socioeconomic change and climate change for California.

2.1. Limitations

A number of important limitations are inherent in such a study of climate change:

- We are uncertain about how socioeconomic conditions will change. Different sets of socioeconomic conditions can have markedly different consequences not only for greenhouse gas emissions but also for how society will be affected by climate change.
- We know that climate will change, but exactly how it will change is unclear. Uncertainty about such important factors as regional and local precipitation and change in climate variability (e.g., frequency and intensity of extreme events) makes it difficult to predict many climate change impacts.
- We are uncertain about many biophysical responses, particularly about how vegetation will respond to changes such as higher carbon dioxide (CO₂) concentrations in the atmosphere. CO₂ can increase plant growth and reduce demand for water. We do not know exactly how forests and crops will respond to higher CO₂ concentrations, particularly if drought or other adverse conditions increase.
- We do not know exactly how society will respond to climate change. By necessity, these studies make assumptions about how individuals and governments will respond to climate change impacts. Although these assumptions are reasonable, individual responses could differ.

These general limitations apply to all the sector studies, and the sector summaries in Section 3.0 present key limitations that are unique to the individual sectors.

2.2. Socioeconomic And Climate Change Scenarios

2.2.1. Socioeconomic Scenarios

California experienced tremendous population and economic growth in the 20th century, transforming the state from a mostly rural one that depended on extracting natural resources to a highly urbanized one with strong high-technology and service sectors. These changes have placed much greater demand on natural resources such as water and land. Such changes in socioeconomic conditions can substantially alter the vulnerability of a society to climate change (in many respects reducing risk, such as through income growth, and in other ways increasing risk, such as through population growth). To determine the future vulnerability of California to climate change, a vulnerability assessment should consider not only climate change but also societal and economic change (see, for example, Parry and Carter, 1998; Mendelsohn and Neumann, 1999). Important socioeconomic factors that could affect vulnerability to climate change include changes in population, income, how much of the economy is directly sensitive to climate (e.g., agriculture), land use, and public demand for environmental services (e.g., clean air and water for recreational purposes). The socioeconomic scenarios used in these studies make assumptions for the first four of these factors (see Appendix II for a summary of the public workshop where these scenarios were discussed). Changes in the demand for

environmental services were viewed as potentially important, but were not explicitly addressed in any of the analyses.

Population. California's population is projected to continue increasing throughout this century. The U.S. Census Bureau (2001) estimates that the state's population will grow from 32.5 million in 2000 to 49.0 million by 2025, and there is little reason to believe that the population will not continue to grow beyond 2025 (Johnson, 1999). Based on a workshop with experts on socioeconomic trends in California, we developed two population scenarios to capture a wide range of growth possibilities. In one scenario, population reaches 67 million by 2060 and 92 million by 2100. In a second scenario, population stabilizes at 67 million by 2060. The key uncertainty underlying these scenarios is the rate of immigration, because fertility and mortality rates among native-born Californians are expected to remain low.

Income. Per capita income is assumed to continue increasing, but the degree to which it does so is likely to be affected by the rates of population growth and immigration. We assumed that the higher population-growth scenario results from lower-income individuals immigrating to the state. Based on this, we assumed that per capita income would grow 2% per year under the low population-growth scenario and 1% per year under the high population-growth scenario.

Share Of Economy In Climate-Sensitive Activities. In this century, the relative importance of economic sectors in California will most likely shift, changing the nature of the state's vulnerability to climate change. For example, the share of the economy in many sectors that are directly sensitive to climate, such as agriculture and timber, is likely to decline. On the other hand, the share of the economy in such climate-sensitive sectors as tourism and recreation is likely to grow as per capita income continues to increase.

Land Use. With the tremendous assumed growth in population, demand for land for new residences is likely to increase. A key issue is how much additional land will be needed. This will be determined by the proportion of the additional demand that will be met through infill and more dense housing versus the proportion that will be satisfied by converting substantial amounts of agricultural or natural lands to residential areas. The change in land use will have consequences for water use, agriculture, and biodiversity. Appendix III by Landis and Reilly describes the potential changes in land use for urban and suburban uses over the next 100 years. These land use estimates are considered in the agriculture, water, and biodiversity impact studies.

Landis and Reilly estimated changes in land use patterns at the 1 ha level arising from the population growth scenarios mentioned above. Their model considered:

- Changes in demand (changes in income and jobs)
- Physical and land use characteristics (such as slope, flood zone, and freeway access)
- Adjacency and neighborhood variables (which consider the environmental and land use characteristics of adjacent and neighboring areas)
- Regulatory and administrative variables (which account for policies that limit or encourage development).

The baseline scenario used in this analysis assumes no change in land use policies and no construction of new freeways or highways.

Landis and Reilly built regional models for southern California, northern California, the Sacramento region, and the San Joaquin Valley. Their analysis includes assumptions about the development of new job growth centers, forecasts of change in county population, and assumptions about infill and population densities.

Figure 10 shows the results of their analysis. Most of the growth is projected in southern California, in the San Francisco Bay area, and in the Central Valley. Areas such as Los Angeles and San Francisco are close to being built out, so much of the growth is projected in inland areas.

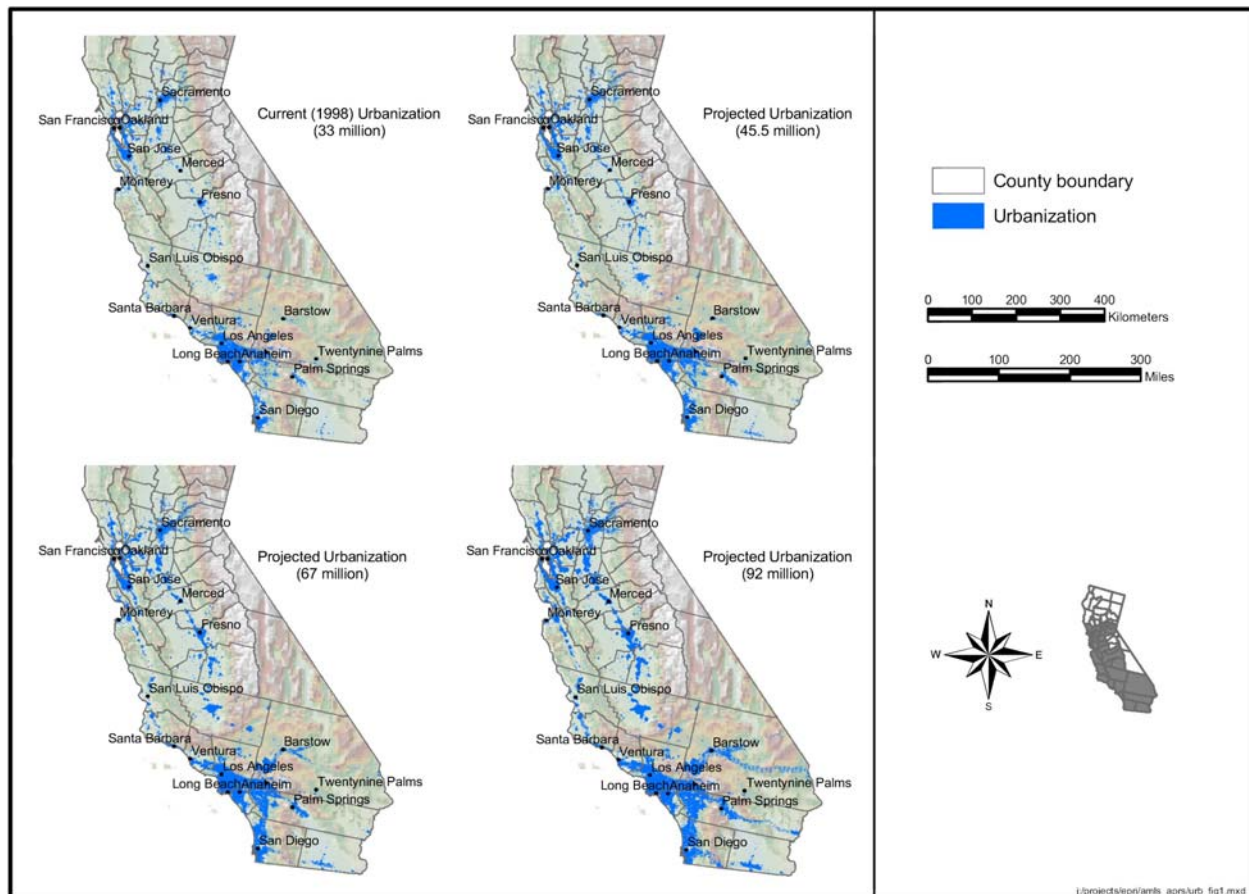


Figure 10. Estimated Distribution Of Urban Areas Under 33 Million (1998), 45.5 Million, 67 Million, And 92 Million Scenarios

These scenarios do help us understand how changes in socioeconomic conditions will affect vulnerability to climate change. Nonetheless, there is substantial uncertainty about how socioeconomic factors such as population, and particularly income and land use, will change during the century. Improving forecasts of changes in these factors will help us better comprehend not only the state's vulnerability to climate change but also the challenges and opportunities presented by these changes.

2.2.2. Climate Change Scenarios

Making credible predictions about how California's climate will change during this century is not possible. Climate models are unable to make definitive statements about how regional climate will change, although their capability is improving (Kerr, 2001). Typically, studies of potential climate change impacts develop plausible scenarios of climate change to help identify the sensitivities of affected systems. The scenarios should meet two criteria:

1. They should be physically consistent with scientific understanding about how global climate will change.
2. They should represent a broad, plausible range of change in climate. Using a narrow range of scenarios may convey more certainty about the future than is scientifically justified.

Under the aegis of this project, at the meeting held in Sacramento on June 12-13, 2000, climate change and impacts assessment experts reviewed the state of knowledge on climate change in California (see Appendix I for a summary of this workshop). An analysis conducted for the workshop showed that most general circulation models (GCMs) estimate that with increased greenhouse gas concentrations, California's climate will get wetter, some projecting a doubling of precipitation by 2100. Other GCMs estimate that precipitation in the state will remain about the same or decrease. The results of more recent analysis are that the GCMs do not show a consistent change in annual precipitation in California. To add uncertainty, one GCM operated under different plausible initial conditions can project that California will become wetter under one set of assumptions and project that the state will become drier under a different set of assumptions. Even though they may disagree on whether precipitation will increase or decrease in California, most of the models agree on the seasonal pattern of changes, estimating that winter precipitation will increase and summer precipitation – which is already quite low across the state – will decrease. Participants at the scenario meeting agreed that the climate scenarios chosen should reflect this wide range of potential changes in climate, including a scenario that projects a much wetter future and one that projects a drier future.

To represent the range of uncertainty from the reviewed projections, we selected a combination of two GCM runs and a set of uniform incremental scenarios (which assume uniform changes in the historical climate data for all temporal and geographical scales). Because of the limited results currently available from regional climate models (RCMs) and statistical downscaling, we decided to base the scenarios on GCM results. The GCMs provide more spatial and temporal variance, but are quite data intensive. For example, the GCMs give different estimates of climate change for each season for each region in California. The uniform scenarios assume the same change in each season and across the entire state and so are easy to develop and interpret, but lack the spatial and temporal differences that the GCMs estimate. Ideally, we would like to combine estimates in changes in climate variability with the uniform scenarios. However, although the workshop attendees thought that climate variability would also change, information on which to base plausible changes in variability is currently insufficient.

The GCM runs selected are:

- The relatively wet and warm Hadley Climate Model, version 2 (hadcm2) scenario (Johns et al., 1997), which was also used in the U.S. National Assessment (NAST, 2000)
- A relatively cooler and drier run from NCAR's PCM (Dai et al., 2001).

Most PCM runs estimate increased annual precipitation for California. Among those GCMs, HadCM2 projects one of the highest increases. To provide a contrast to the wet HadCM2 run, we selected one of the drier PCM runs.

The GCM data are generated for large grid cells ($2.5 \times 3.75^\circ$ for HadCM2 and $2.8 \times 2.8^\circ$ for PCM). These data projections were downscaled to 10 km cells using the procedure described in [Box 1](#) (and Attachment 1 in Appendix I). This downscaling had already been performed for the HadCM2 scenario as part of the U.S. National Assessment (NAST, 2000). The PCM results had to be downscaled specifically for this project. To provide a clearer perspective on the various grid resolutions, Figure 1 displays the resolution at GCM scale, at 50 km, and at 10 km (the figure displays land use in California using grid boxes at the three different resolutions).

Box 1: Procedure For Developing GCM-Based Climate Change Scenarios

1. The GCM scenarios were statistically interpolated (downscaled) to a 10 km (100 km²) grid. Although the downscaling allows for more disaggregation of results, it does not completely capture how California's microclimates may change in the future.
2. The GCM output for the base period (1961-1990) was subtracted from or divided into the GCM output from three periods in the transient run:
 - ▶ 2010-2039
 - ▶ 2050-2079
 - ▶ 2080-2099.
3. The changes in temperature were added to an observed data set of temperature at the 10 km level and the precipitation ratios were multiplied by observed precipitation. By using the full transient, this approach allows for change in interannual variability and seasonal climate. It does not allow for changes in daily climate or in the diurnal cycle. Note that some studies used average change in climate in the three time periods listed above. These studies assumed that interannual climate would not change from the observed period.

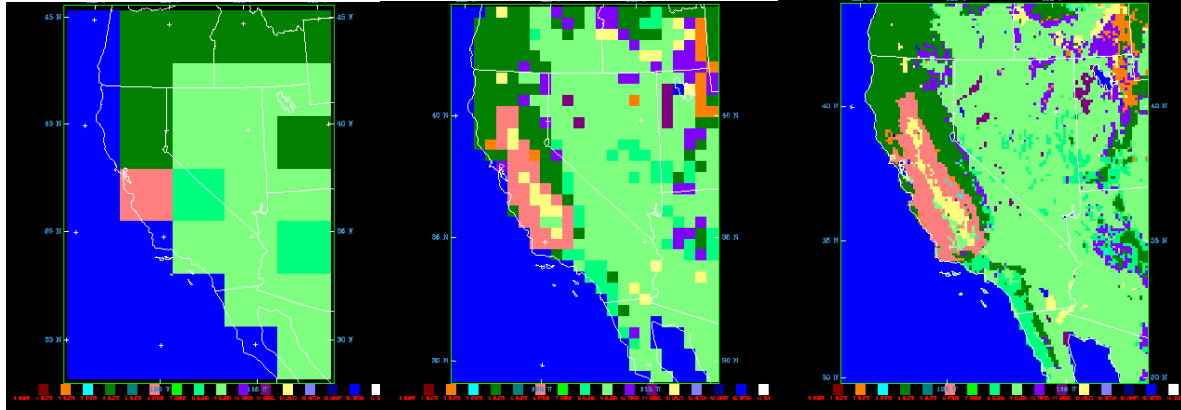


Figure 11. Resolution at GCM scale, 50 km, and 10 km

The uniform scenarios provide a greater range of change in temperature and precipitation than do the two GCMs. This is particularly important because even though the two GCMs capture a wide range of precipitation changes, they capture only a narrow range of temperature increases. By using the incremental scenarios, we were able to examine a broader range of scenarios than if we had relied solely on GCMs. One set of uniform scenarios assumes that the precipitation will increase in proportion to the rise in temperature. This was based on analyzing the average change in precipitation per degree of warming for California from more than 20 GCMs (see Appendix I). The other set of uniform scenarios assumes no change in precipitation.

Error! Not a valid bookmark self-reference. presents the GCM and uniform scenarios. Figure 12 and Figure 13 display the changes in temperature and precipitation from the present day through the end of the century at the 10 km scale level for the HadCM2 and PCM GCMs, respectively, displaying wet season (November through March) and dry season (June through August) months.

Table 6 California 2100 Climate Change Scenarios for This Assessment

California 2100 Climate Change Scenarios for This Assessment		
GCM Scenario	Incremental Scenarios	
	Change in Temperature (°C)	Change in Precipitation (%)
GCM		
HadCM2	+3.3	+58
PCM	+2.4	-21
Incremental		
1.5°C, 0% P	+1.5	+0
1.5°C, 9% P	+1.5	+9
3°C, 0% P	+3	+0
3°C, 18% P	+3	+18
5°C, 0% P	+5	+0
5°C, 30% P	+5	+30

Even though these scenarios cover a broad range of potential changes in climate, more work is needed to develop scenarios with high spatial resolution that also capture potential changes in multiyear climate events (such as El Niño events) and in daily to monthly events (such as storms and droughts). Decision makers would find the scenarios much more useful if we could reasonably assign probabilities to them, instead of treating them as equally plausible.

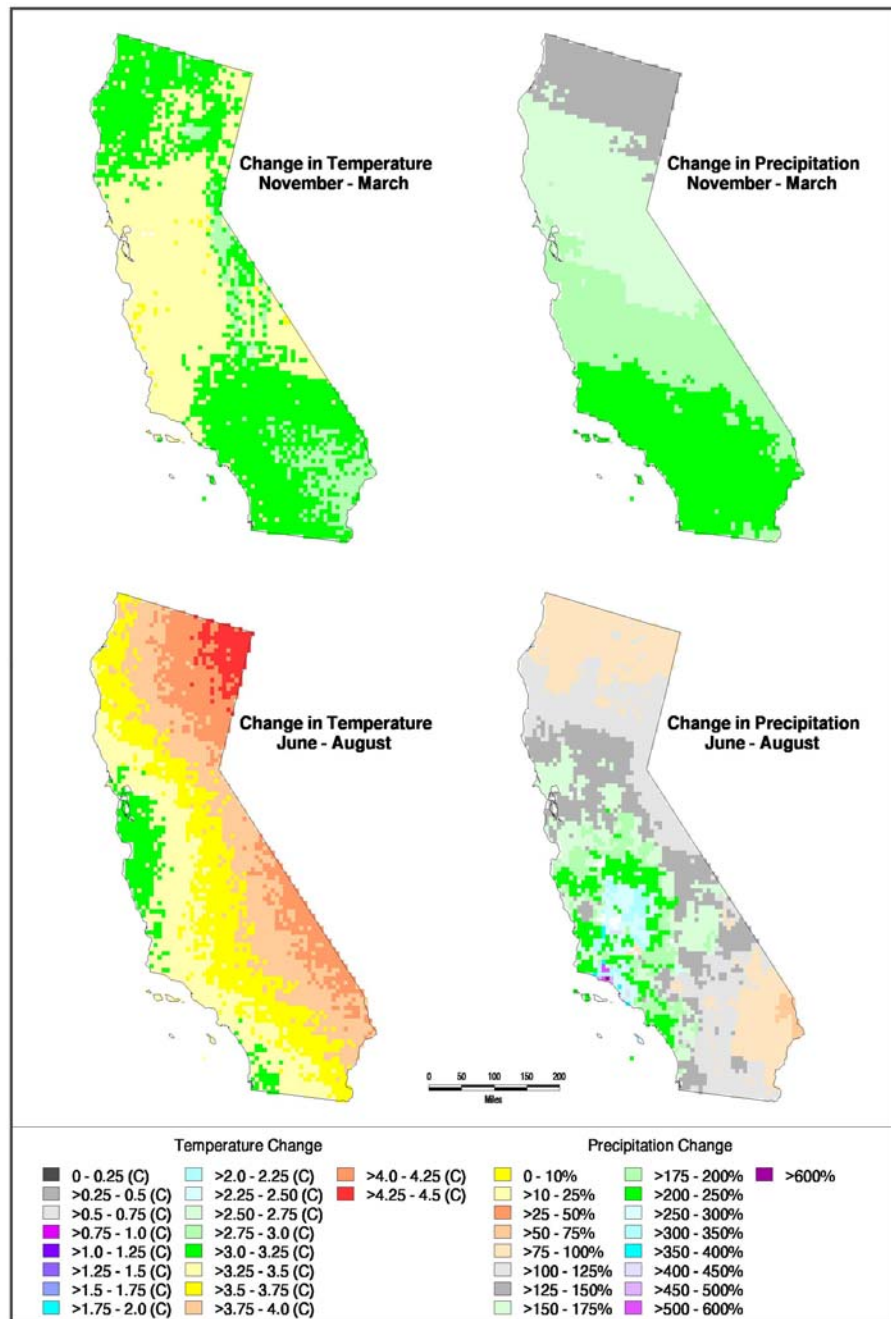


Figure 12. Hadcm2 Estimated Changes In Wet (Top) And Dry (Bottom) Seasonal Precipitation And Temperature For 2080-2099 Compared To Modeled Baseline Years 1960-1990 At 10 Km Resolution

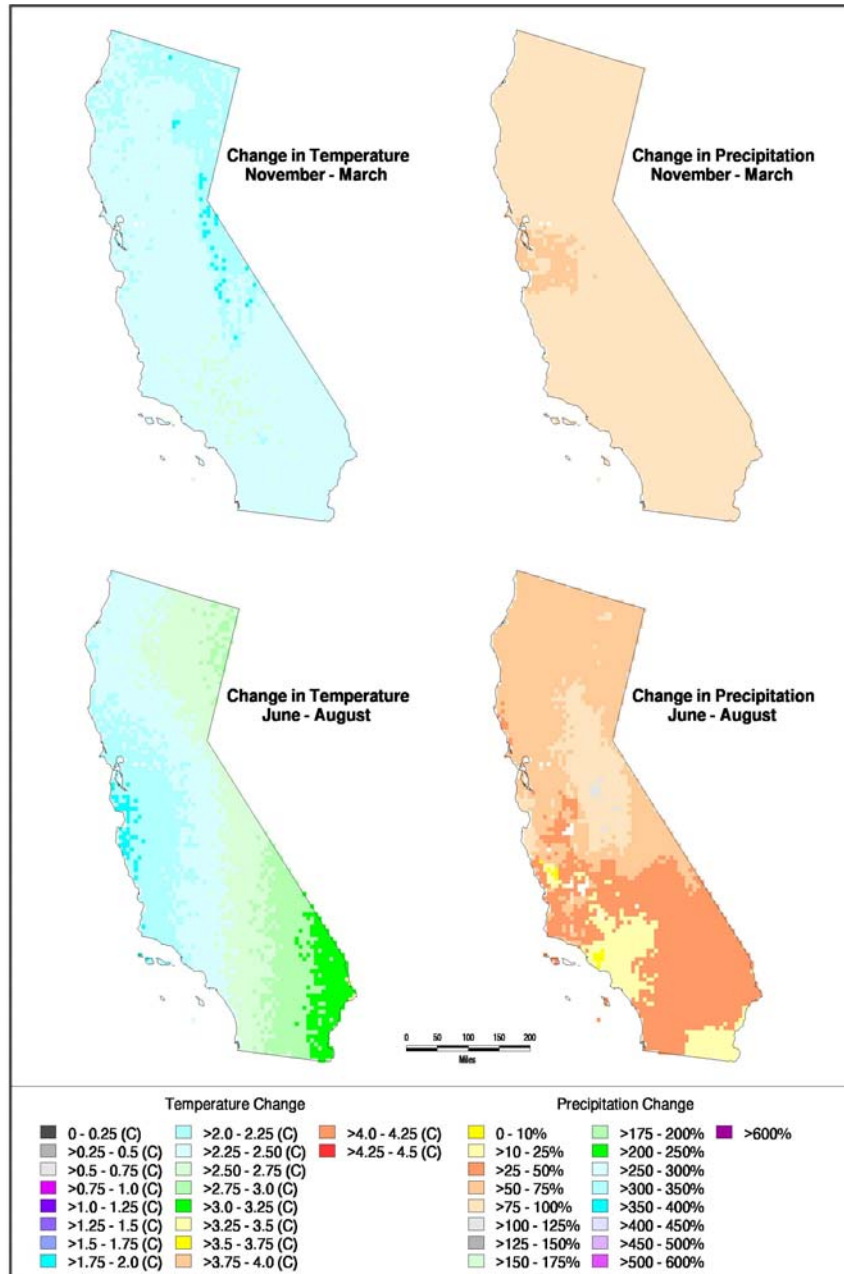


Figure 13. PCM Estimated Changes In Wet (Top) And Dry (Bottom) Seasonal Precipitation And Temperature For 2080-2099 Compared To Modeled Baseline Years 1960-1990 At 10 Km Resolution

3.0 Project Outcomes

This section summarizes the results from the individual studies conducted as part of this project. First, we present potential changes in terrestrial vegetation and discuss the implications of these changes for biodiversity and timber production. Next, we explore how climate change may affect runoff. Changes in runoff, in turn, will affect the water supply for urban and industrial users and for agriculture. Combining changes in irrigation water demand and changes in crop yields, the models measure the potential effects of climate change on California agriculture. In the final part of this section, we turn to potential impacts on energy and coastal

resources, and review an initial study of the historical relationship between climate variability and health in California.

3.1. Terrestrial Vegetation

3.1.1. Introduction

Three studies explore the effects of climate change on California's terrestrial vegetation and examine the potential biophysical and socioeconomic implications in greater detail and more comprehensively than has been done before. The first estimates changes in the location and productivity of terrestrial vegetation. The second study combines the results of these ecosystem analyses with estimates of change in land use to examine implications for biodiversity. The third study uses the results of the ecosystems analyses to estimate changes in timber production.

3.1.2. Ecosystems

To estimate how the location and productivity of California's terrestrial vegetation could change through the rest of this century, this study (see Appendix IV) uses the MC1 model (Daly et al., 2000). The MC1 is a dynamic general vegetation model that brings together vegetation distribution data from a biogeography model, MAPSS; carbon and nutrient dynamics from a biogeochemistry model, CENTURY; and information yielded by a new dynamic fire model.

This study advances the analysis of climate change impacts on vegetation by applying the MC1 model at a 100 km² resolution, the highest resolution at which a dynamic model has been applied in California. In addition, because the project focused on one state, it considered more classes of vegetation.

MC1 simulates vegetation change over large areas through time while estimating variability in the carbon budget and responses to episodic events such as drought and fire. The model does not incorporate all processes that could influence future responses to climate change. For instance, it does not consider the speed at which vegetation types could migrate to new locations, or barriers to migration such as mountains or water bodies. However, given the heterogeneity of California's current ecosystems (see Figure 14), we can reasonably expect that many species within a vegetation class will be able to migrate to new locations, as is assumed in the analysis. MC1 does not account for changes in the prevalence of diseases or pests, some of which could occur rapidly under climate change and affect vegetation. On the whole, the model does represent the state of the art in modeling ecological responses to climate change. Improvements in vegetation models should address species migration and change in disease and pests.

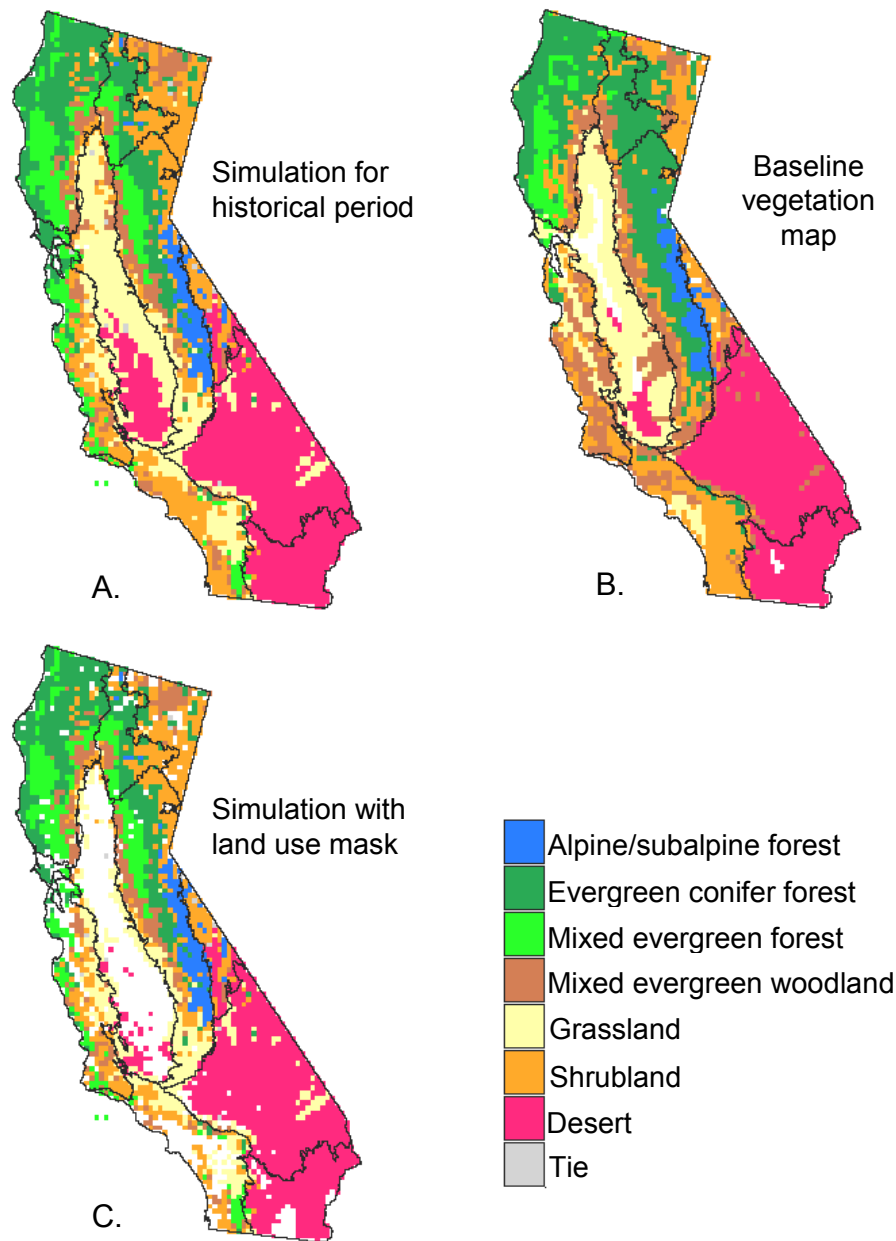


Figure 14. Maps Of The (A) Distribution Of The Simulated Vegetation Classes For The Historical Period (1961-1990), (B) Baseline Vegetation Map, And (C) Historical Simulation With Urban And Agricultural Areas Masked Out. The vegetation class mapped at each grid cell in (a) and (c) is the most frequent class simulated during the historical period. A "tie" is where two or more classes were equally frequent.

Distribution Of Ecosystems

Figure 15a shows the vegetative distribution simulated by MC1 for the historical period, 1961-1990; Figure 15b shows the corresponding vegetative distribution for the 2070-2099 period, assuming the HadCM2 climate scenario. The most prominent feature of the response of vegetation distribution under the substantially wet HadCM2 scenario was the expansion of conifer and mixed evergreen forests, along with grasslands. The expansion of these vegetation

types came at the expense of shrublands, arid land vegetation, and to a lesser extent, mixed evergreen woodland and alpine/subalpine forest. The expansion of forests was most notable on the Modoc Plateau, in the northern Central Valley, at higher elevations in the Sierra Nevada, and inland along the coast. Increases in both temperature and moisture under the HadCM2 scenario favored expansion of forests, with increasing temperatures being the critical factor allowing vegetation zones to move higher in the Sierra Nevada. In one interesting projection, mixed evergreen forest replaced conifer forest in much of the northern half of the state. Although conifer forest retreated over much of its range, the total coverage of conifer forest did not change much because of its expansion on the Modoc Plateau and along the eastern side of the Sierra Nevada. Another projection of possible conservation interest is the expansion of conifer forest inland along the central coast. In the coast's maritime environment, this could occur as an expansion of redwood forests inland at the expense of Douglas-fir/tan-oak forest or canyon-live-oak/madrone forest.

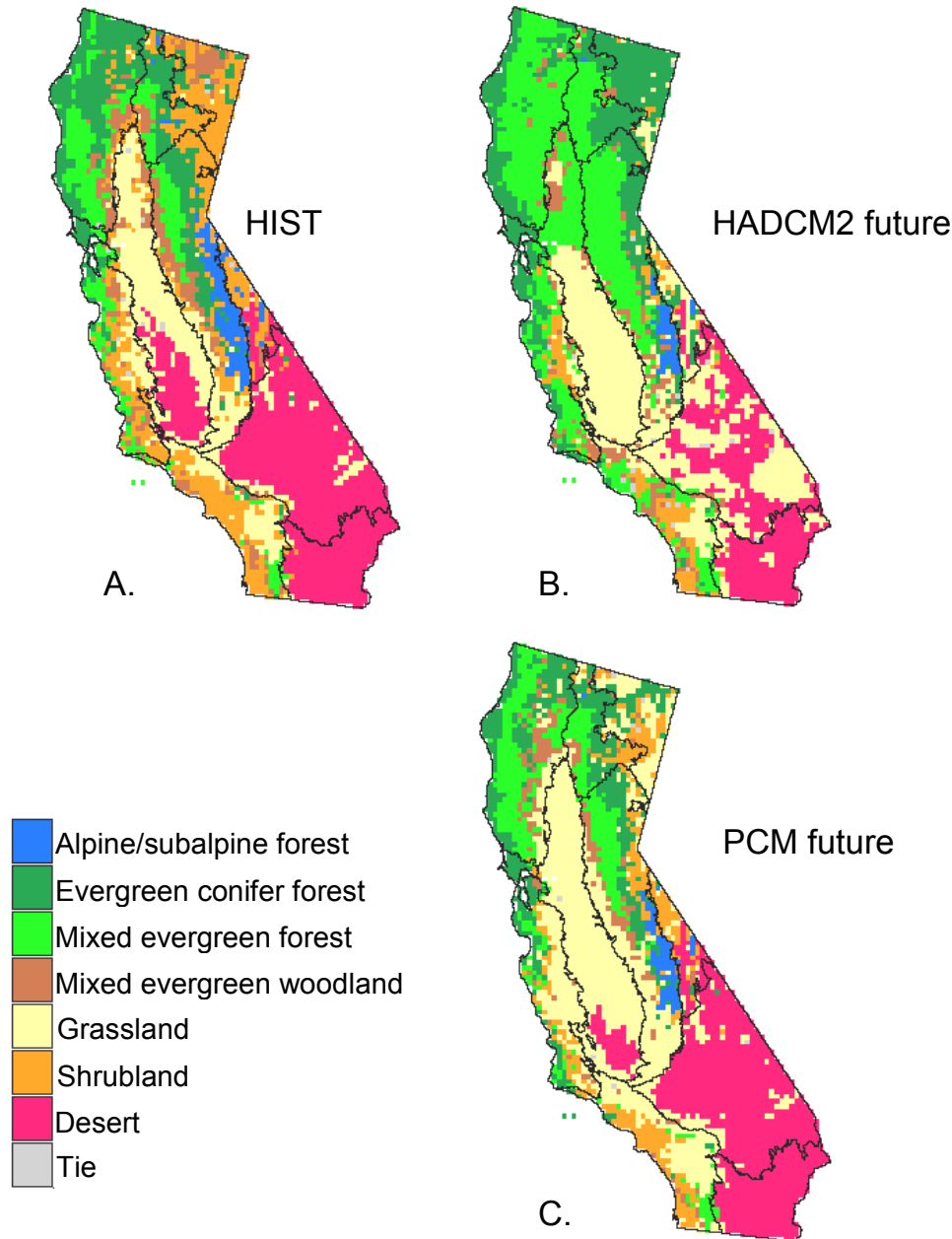


Figure 15. Distribution Of The Vegetation Classes (A) Simulated For The Historical Period (1961-1990) And (B,C) The Future Period (2070-2099) Of The Hadcm2 And PCM Climate Scenarios. The vegetation class mapped at each grid cell in is the most frequent class simulated during the time period. A “tie” is where two or more classes were equally frequent.

Distribution of ecosystems

Figure 15 shows the vegetative distribution simulated by MC1 for the historical period, 1961-1990; Figure 7b shows the corresponding vegetative distribution for the 2070-2099 period, assuming the HadCM2 climate scenario. The most prominent feature of the response of vegetation distribution under the substantially wet HadCM2 scenario was the expansion of conifer and mixed evergreen forests, along with grasslands. The expansion of these vegetation

types came at the expense of shrublands, arid land vegetation, and to a lesser extent, mixed evergreen woodland and alpine/subalpine forest. The expansion of forests was most notable on the Modoc Plateau, in the northern Central Valley, at higher elevations in the Sierra Nevada, and inland along the coast. Increases in both temperature and moisture under the HadCM2 scenario favored expansion of forests, with increasing temperatures being the critical factor allowing vegetation zones to move higher in the Sierra Nevada. In one interesting projection, mixed evergreen forest replaced conifer forest in much of the northern half of the state. Although conifer forest retreated over much of its range, the total coverage of conifer forest did not change much because of its expansion on the Modoc Plateau and along the eastern side of the Sierra Nevada. Another projection of possible conservation interest is the expansion of conifer forest inland along the central coast. In the coast's maritime environment, this could occur as an expansion of redwood forests inland at the expense of Douglas-fir/tan-oak forest or canyon-live-oak/madrone forest.

In addition to the widespread advancement of forest, another feature of the response of vegetation distribution under the HadCM2 scenario was the advancement of grassland, particularly in the southern end of the Central Valley and in the uplands of the Mojave Desert, where grassland replaces desert vegetation. Here the response to increased precipitation would have favored an increase in both tree and grass biomass, but because of the importance of fire, grasses end up dominating.

The PCM climate scenario, with a smaller increase in temperature and drier conditions, resulted in far less dramatic changes in vegetation. The most prominent feature of the vegetation response to the PCM scenario (Figure 15c) was the advancement of grassland into the simulated historical range of mixed evergreen woodland and shrubland. This transition was prompted by a decline in the competitiveness of woody plants relative to grasses as a response to a decline in moisture, along with an increase in fire that further constrained woody plants. The advancement of grassland occurred primarily on the Modoc Plateau, in the foothills surrounding the Central Valley, and along the east side of the southern coast ranges. Mixed evergreen woodland and shrubland both retreat somewhat under the PCM scenario. In contrast to the simulation for the HadCM2 scenario, the distributions of mixed evergreen forest and conifer forest remained relatively static under the PCM scenario.

The common response of the vegetation classes under the incremental scenarios (not pictured) was an increase in the total coverage of mixed evergreen forest and grassland classes and a decrease in the coverage of the other five classes. The mixed evergreen forest responded to the warmer temperatures by advancing into the historical range of conifer forest. Mixed evergreen forest also responded to the wetter scenarios (3°C, 18% P and 5°C, 30% P) by advancing into the historical range of mixed evergreen woodland.

Grassland responded to the drier scenarios (3°C, 0% P and 5°C, 0% P) by advancing into the mixed evergreen woodland and shrubland classes. The decrease in moisture favored grass over woody life forms at the boundaries between grassland and these two vegetation classes. Grassland responded to the wetter scenarios (3°C, 18% P and 5°C, 30% P) by advancing into desert.

Losses in the coverage of evergreen conifer forest to the advancement of mixed evergreen forest under all incremental scenarios were partially counterbalanced by gains in the Modoc Plateau and eastern Sierra Nevada regions. Here warmer and especially wetter conditions prompted an increase in woody carbon density and a resultant expansion of conifer forest into woodland and

shrubland. The net result of this retreat and advancement of evergreen conifer forest ranged from nearly no change in coverage under the most cool and wet scenario (3°C, 18% P) to the greatest decrease under the most warm and dry scenario (5°C, 0% P).

Mixed evergreen woodland and shrubland responded with nearly uniform losses of coverage under all the incremental scenarios. Losses under the drier scenarios (3°C, 0% P and 5°C, 0% P) were mostly to the advancement of grassland. Under the wetter scenarios (3°C, 18% P and 5°C, 30% P), losses were typically to the advancement of the mixed evergreen and evergreen conifer forest classes.

Carbon Storage

Changes in the amount of area covered by different vegetation types may result in changes in the amount of carbon stored in ecosystems (Figure 8a). Changes in carbon storage in vegetation (Figure 8b) are likely to occur when there is a transition to a vegetation type with more or less woody biomass or simply as a result of change in growth or productivity.

Not surprisingly, under the HadCM2 scenario, virtually all of California experienced an increase in the amount of carbon stored in vegetation, and total ecosystem carbon increased in many areas (Figure 8). In many areas, the increase in carbon accompanied the transition from shrublands or woodlands to forest (e.g., the Modoc Plateau, the foothills around the Central Valley, and along the central coast). For the state as a whole, there is about a 5% increase in total ecosystem carbon storage and an increase of 23% in vegetation carbon (Table 7).

The results under the PCM scenario were somewhat different (Figure 16 and Table 7). Total ecosystem carbon actually increased more under the PCM scenario than in the HadCM2 scenario, with most of the increase coming in litter and soil carbon. This is the result of the estimated expansion in grasslands, which store relatively large amounts of carbon in soils. For vegetation carbon, some parts of the state experienced modest increases in carbon storage and others had decreases. The only areas that experienced very large percentage increases in vegetation carbon were along the coast, and these large increases were often seen where forests replaced shrublands. The largest decreases in both total and vegetation carbon occurred mainly in the deserts.

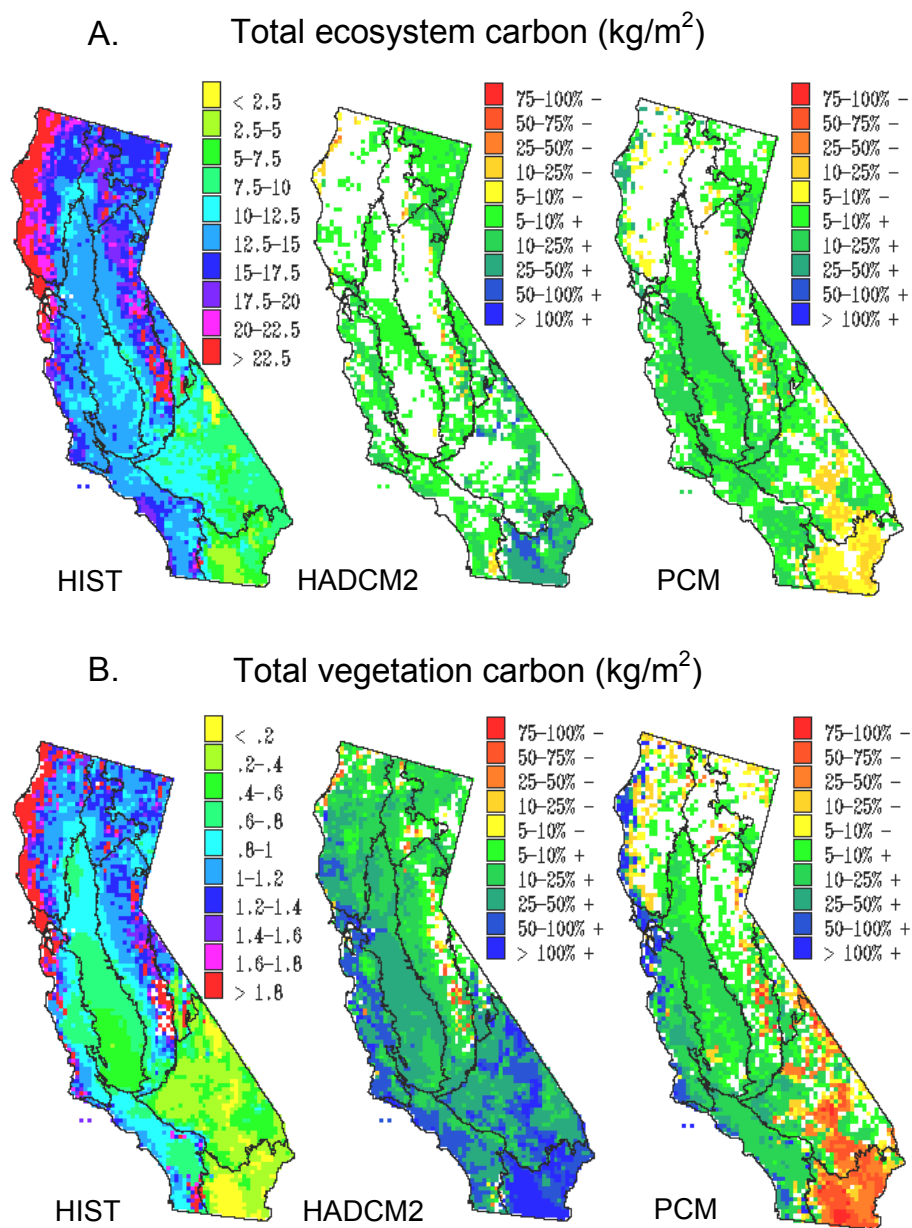


Figure 16. The Distribution Of (A) Average Total Ecosystem Carbon And (B) Average Annual Total Vegetation Carbon For The Historical Period (1961-1990) Simulation And For Simulated Changes In Same For The Future Period (2070-2099) Of The Hadcm2 And PCM Climate Scenarios Future changes are relative to the historical period

Table 7. Size Of The Historical Carbon Pools Simulated For California And Future Changes In Size Simulated Under The Hadcm2 And PCM Climate Scenarios^a

Size Of The Historical Carbon Pools Simulated For California And Future Changes In Size Simulated Under The Hadcm2 And PCM Climate Scenarios^a			
Carbon Pool	Historical (Tg)	Hadcm2 Change (% Change)	Pcm Change (% Change)
Total Ecosystem	5765	+312 (5%)	+325 (6%)
Soil And Litter	5305	+203 (4%)	+246 (5%)
Total Live Vegetation	461	+107 (23%)	+78 (17%)
Live Wood	300	+99 (33%)	+38 (13%)
Live Grass	163	+9 (6%)	+41 (25%)
a. Historical values in teragrams are the mean weights for the 30 year (1961-1990) base period. HadCM2 and PCM change values in teragrams are the mean weights for the 30 year (2070-2099) future period subtracted from the mean weights for the historical period.			

For the incremental scenarios, data are reported only as statewide totals (Table 8). For all four scenarios, there are small increases in total ecosystem carbon and slightly larger increases for the scenarios with increased precipitation (3°C, 18% P and 5°C, 30% P). Vegetation carbon also increased under all four scenarios, and the increases were larger for the two wetter scenarios, presumably as a result of the expansion of forests.

Table 8. Simulated Total Carbon Density For The State In Different Carbon Pools Averaged Over The 1961-1990 Historical Period, And Percentage Changes In The Different Pools Under The Incremental Scenarios

Simulated Total Carbon Density For The State In Different Carbon Pools Averaged Over The 1961-1990 Historical Period, And Percentage Changes In The Different Pools Under The Incremental Scenarios					
Carbon Pool	Historical (Tg)	3°C change (%)		5°C change (%)	
		0% P	18% P	0% P	30% P
Total Ecosystem	5765	+4.8	+5.2	+2.7	+3.5
Soil And Litter	5305	+4.6	+4.7	+2.7	+2.9
Total Live Vegetation	461	+6.5	+10.6	+2.8	+10.0
Live Wood	300	-3.7	+3.3	-8.3	+4.7
Live Grass	163	+25.8	+23.9	+23.3	+20.3

Taken together, the GCM and incremental scenarios project increases of 2.7% to 5.6% in total ecosystem carbon, and the agreement across all scenarios means that the natural ecosystems are likely to sequester some carbon as they respond to climate change. Note that care must be taken in calculations that use these projections to estimate carbon sequestration for the entire state because the analysis does not reflect the effects of anthropogenic land use and land cover change either in the past or the future.

Fire

Fire is a very important ecological factor in California, and, in the absence of development and fire suppression, most areas of the state would be expected to have fire return intervals of 14 years or less (Figure 17a). It is not intuitively obvious how fire frequencies or intensities (Figure 17b) might change as climate changes. In particular, changes in precipitation can have complex effects. For example, an increase in precipitation could reduce fire danger in some areas, depending on when it occurs during the year. Similarly, drier conditions should result in more frequent fires. However, if the increase in precipitation results in an increase in plant growth, building up fuel, fires could be more intense and spread more when they do occur. In addition, changes in fire frequency or intensity will depend heavily on the kind of vegetation present, so changes in vegetation distribution are likely to alter fire regimes. Finally, fire can also influence vegetation features. Even though climate alone might favor trees or shrubs in a particular area, grasslands may end up dominating if fires are frequent.

These state-level totals hide large changes in the patterns of burning. For the HadCM2 scenario, fires became less frequent along much of the coast, presumably as a result of greater precipitation (Figure 17a). Fires became more frequent in the San Joaquin Valley and the desert region. The situation was quite different under the PCM scenario, with most of the state experiencing an increase in fire frequency (Figure 17a). The southwest corner of the state had decreased frequency because the substantial reduction in plant growth and carbon storage resulted in greatly reduced fuels. Under the wet HadCM2 scenario, fire intensity increases, presumably because of the increase in fuel buildup (Figure 17b). In contrast, under the dry PCM scenario, fire intensity decreases because biomass also decreases.

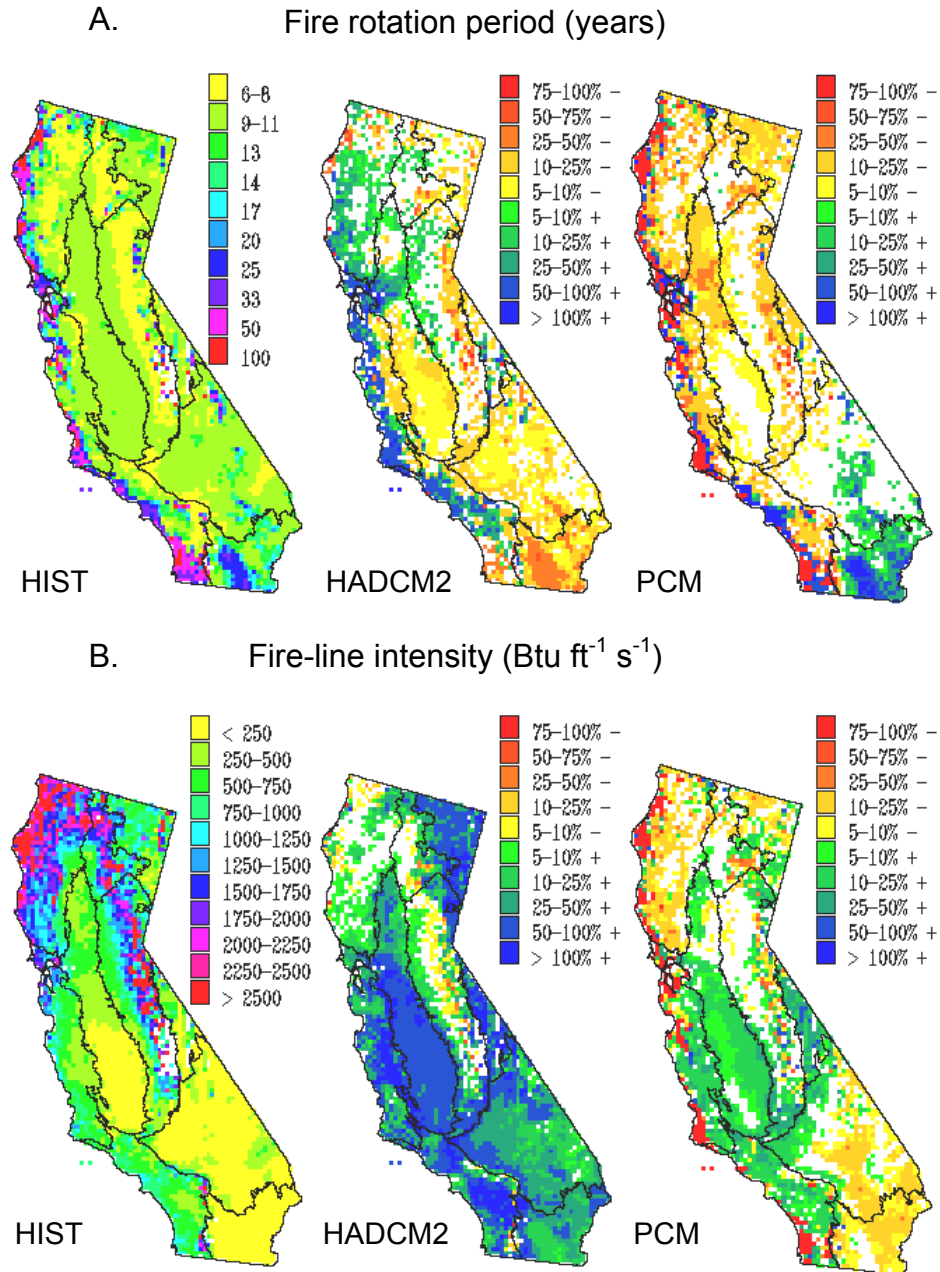


Figure 17. The Distribution Of The (A) Fire Rotation Period And (B) Average Fire-Line Intensity Per Event For The Historical Period (1895-1994) Simulation And For Simulated Changes In Same For The Future Period (2000-2099) Of The Hadcm2 And PCM Climate Scenarios. Future changes are relative to the historical period.

For the state as a whole, the total amount of area that burns annually did not change under either GCM climate scenario during the first 50-60 years of the simulation (Figure 18). After that, drier conditions and the buildup of fuels led to a significant increase in the percentage change from the 100 year historical record under the PCM scenario. For the HadCM2 scenario the annual burned area also increased, but the increase was not significant. However, the simulation projects very serious fire years in 2027, 2044, and 2074. In these years, more area

burns than for any year under the PCM scenario or for any year in the simulated historical period. The somewhat counterintuitive projection that shows more severe fires under the wetter HadCM2 scenario is the result of fuel buildup during wet years. That built-up fuel will burn during occasional dry years.

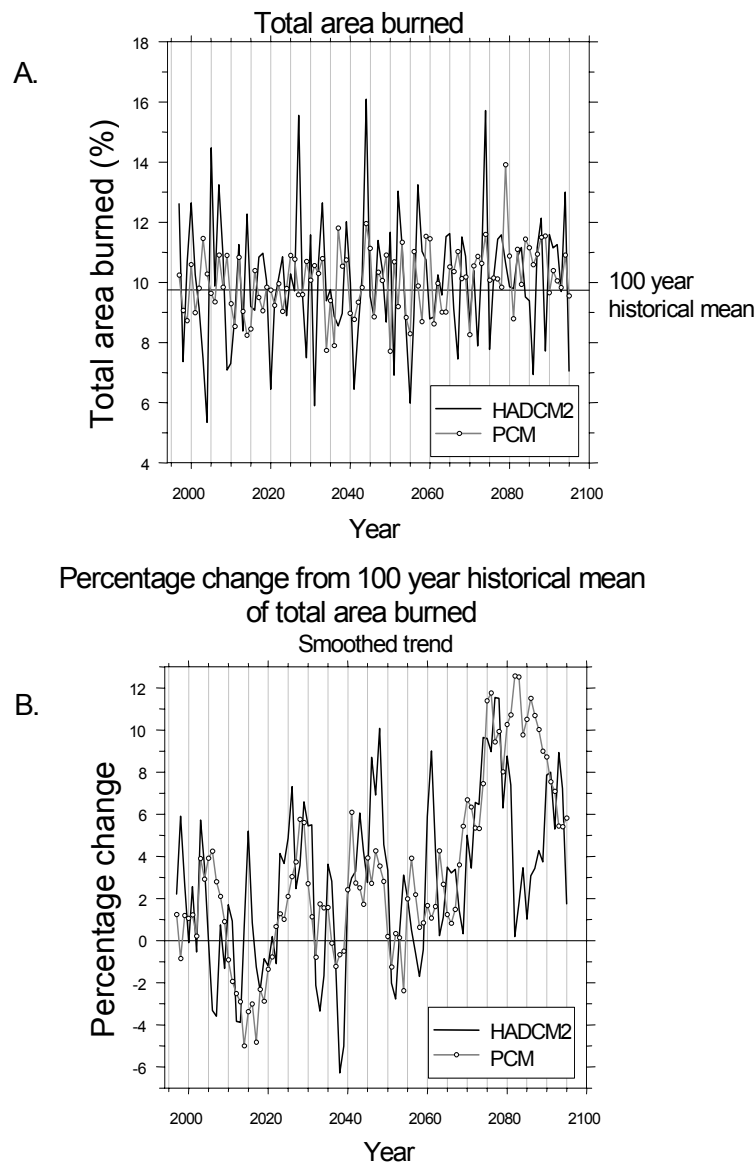


Figure 18. Simulated Trends In (A) The Annual Percentage Of The Total Area Burned And (B) The Smoothed Percentage Deviation From The 100 Year Historical Mean For The Future Period (1994-2099) Of The Hadcm2 And PCM Climate Scenarios

All four incremental scenarios showed a significant increase in the simulated amount of area that burns annually (Figure 19) and a decrease in the fire return period. These scenarios all revealed very similar patterns, with modest decreases in fire return period across most of the state and increases in fire return period confined to a few coastal areas. Here too, the wetter scenarios result in slightly more area burned in fires than do the drier scenarios.

Percent change from 100 year historical mean
of total area burned
Smoothed trends

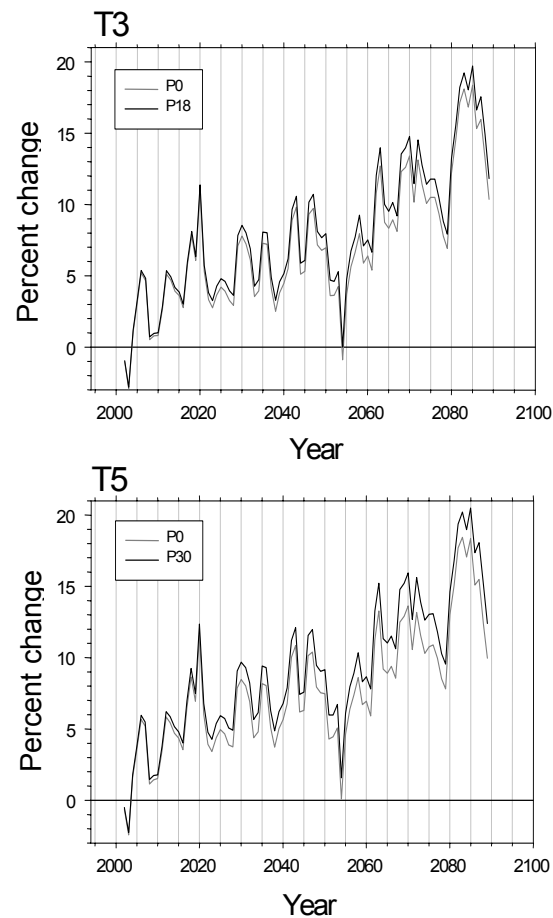


Figure 19. Percentage changes in annual total area burned relative to the 100 year historical mean under the 3°C and 5°C incremental scenarios. Trends were smoothed for display using a 10 year running average.

3.1.3. Land Use And Biodiversity

The study by Galbraith et al. (Appendices V and VI) is one of the first to evaluate at a fairly detailed level the combined effects of climate change and urbanization on the distribution of terrestrial ecosystems. The study's major goal was to determine the cumulative impacts of climate change and urbanization on the state's natural ecosystems. A secondary goal was to understand the relative contributions of climate change and urbanization to projected ecological

change and to evaluate how the two stressors vary in importance over time and among different ecosystems.

Methods

This analysis used the projections of changes in vegetation distribution under future climates developed by Lenihan et al. (Appendix IV) in combination with spatially specific projections of future urban development produced by Landis and Reilly (Appendix III). The results from the two studies were incorporated into a geographic information system (GIS) platform so that they could be overlain. Information on the current distribution of agricultural lands was also incorporated. No projections of future changes in agricultural lands are included in the analysis, but it is likely that the spatial extent of agricultural lands in California will either decrease or remain stable (Wilkinson et al., 2002).

Galbraith and colleagues did not do this analysis for the entire state of California, but for the same area modeled by Landis and Reilly. That area extends from the Central Valley south to the Mexican border and excludes most of the Sierra Nevada.

The investigators used the two different population scenarios (67 million and 92 million; see Appendix III) in their work. Most of this analysis used the high population-growth scenario, and this summary presents results only for that scenario.

Data on the current distribution of urbanization and agriculture were used to “mask out” areas or grid cells where natural vegetation has already been replaced. For all remaining grid cells, the analysis determined whether future urbanization or climate change would affect the natural vegetation. A grid cell was considered to be entirely urbanized if the Landis and Reilly analysis predicted that at least 51% of the land within the cell would become urban. Specifically, there were three possible outcomes in terms of the natural vegetation of any grid cell under a particular climate change scenario: (1) the grid cell does not become urbanized and the vegetation does not change, (2) the grid cell does not become urbanized and the vegetation is projected to change, and (3) the grid becomes mostly urbanized and so is classified as urban with no natural vegetation.

In addition to evaluating the effects of urbanization and climate change on the entire study area and all vegetation types, the investigators conducted a finer resolution analysis for one particular vegetation type — coastal sage scrub (CSS). This vegetation type was selected because it is concentrated in coastal areas that are experiencing extensive urbanization and because it is already of considerable conservation significance. For this analysis, the researchers combined data from the California Gap Analysis Project (GAP; Davis et al., 1998) with the urbanization and potential vegetation projections.

The grid cell size for the Lenihan et al. analysis was 100 km² (10 km on a side), but Landis and Reilly used 1 ha (100 m on a side). To make the data sets compatible, the urbanization projections were scaled up to 100 km². If more than 50% of these hectares were classified as urban, the entire grid cell was classified as urban; if the grid cell was less than 50% urbanized, it was classified as natural vegetation. Because the GAP data set has a spatial resolution of 1 ha, it was directly comparable with the urbanization projections.

Statewide Results

In this summary, only the results for 2100 are presented. The combined effects of climate change and urbanization on the distribution of natural ecosystems can be seen by contrasting maps showing projected vegetation distribution in 2100 under different scenarios (Figure 20 and Figure 21). The chart in Figure 22 summarizes the changes in total acreage for different vegetation categories.

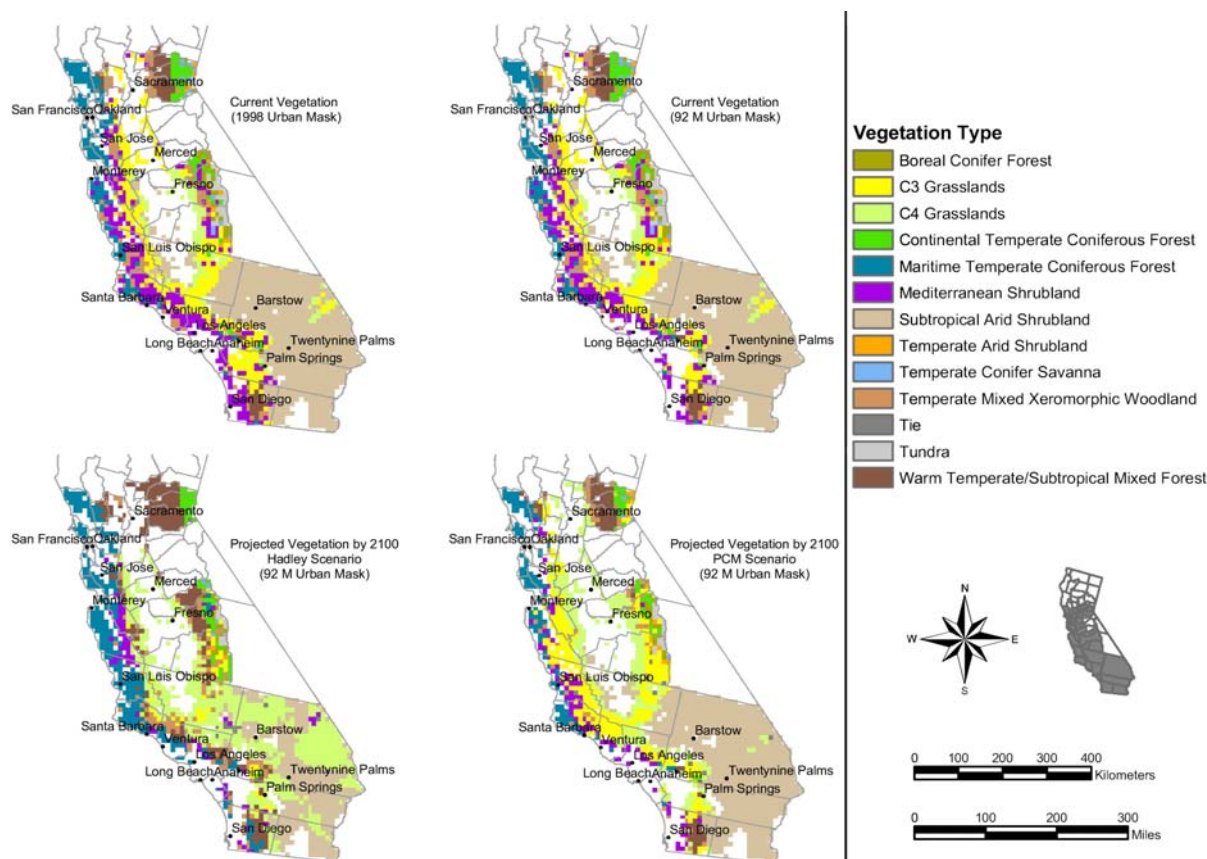


Figure 20. Potential Distribution Of Vegetation Communities Under Current And GCM Climate Change Scenarios. Top-left to lower-right: current modeled vegetation with 1998 urbanization; current modeled vegetation with 92 million population scenario; estimated vegetation by 2100 under the HadCM2 climate change scenario with 92 million population; and estimated vegetation by 2100 under the PCM climate change scenario with 92 million population.

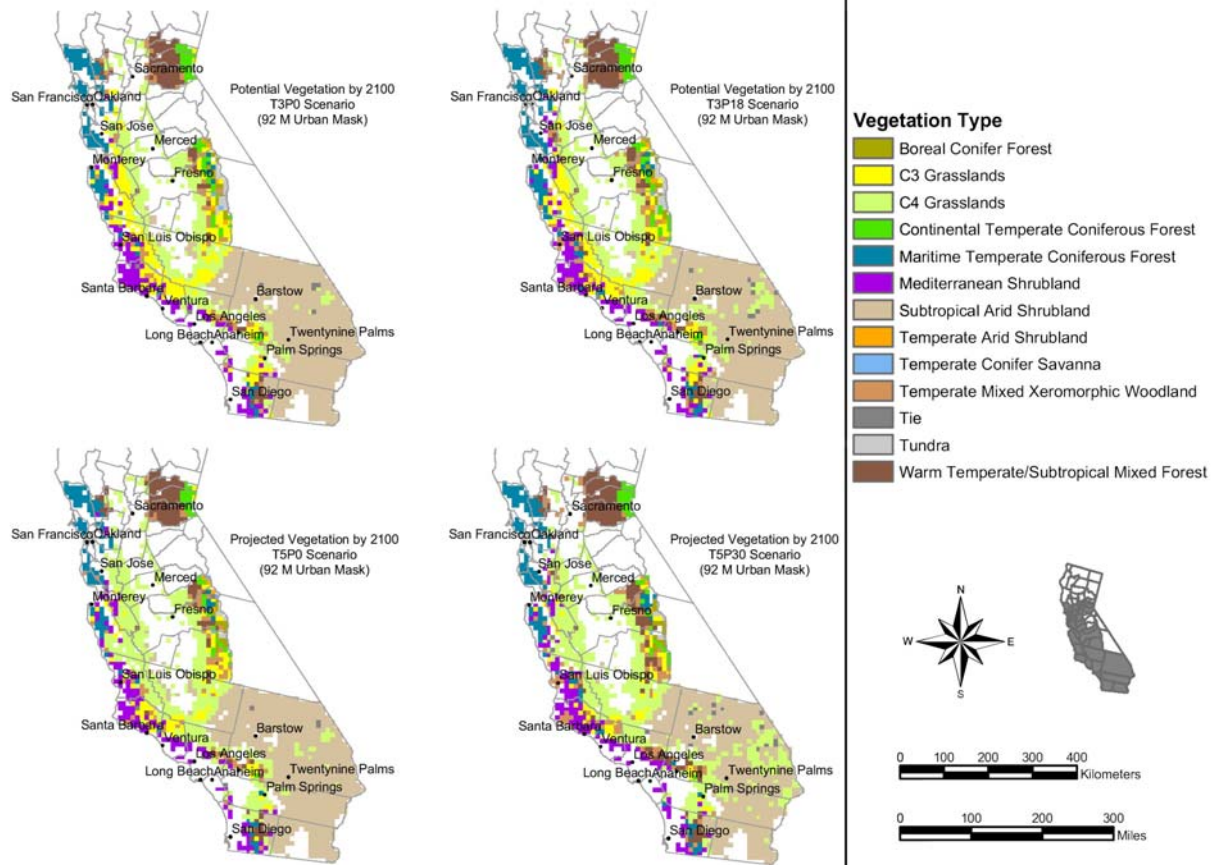


Figure 21. Potential Distribution Of Vegetation Communities Under Incremental Climate Change Scenarios. Top-left to lower-right: estimated vegetation by 2100 under the 3°C, 0% P climate change scenario with 92 million population; estimated vegetation by 2100 under the 3°C, 18% P climate change scenario with 92 million population; estimated vegetation by 2100 under the 5°C, 0% P climate change scenario with 92 million population; and estimated vegetation by 2100 under the 5°C, 30% P climate change scenario with 92 million population.

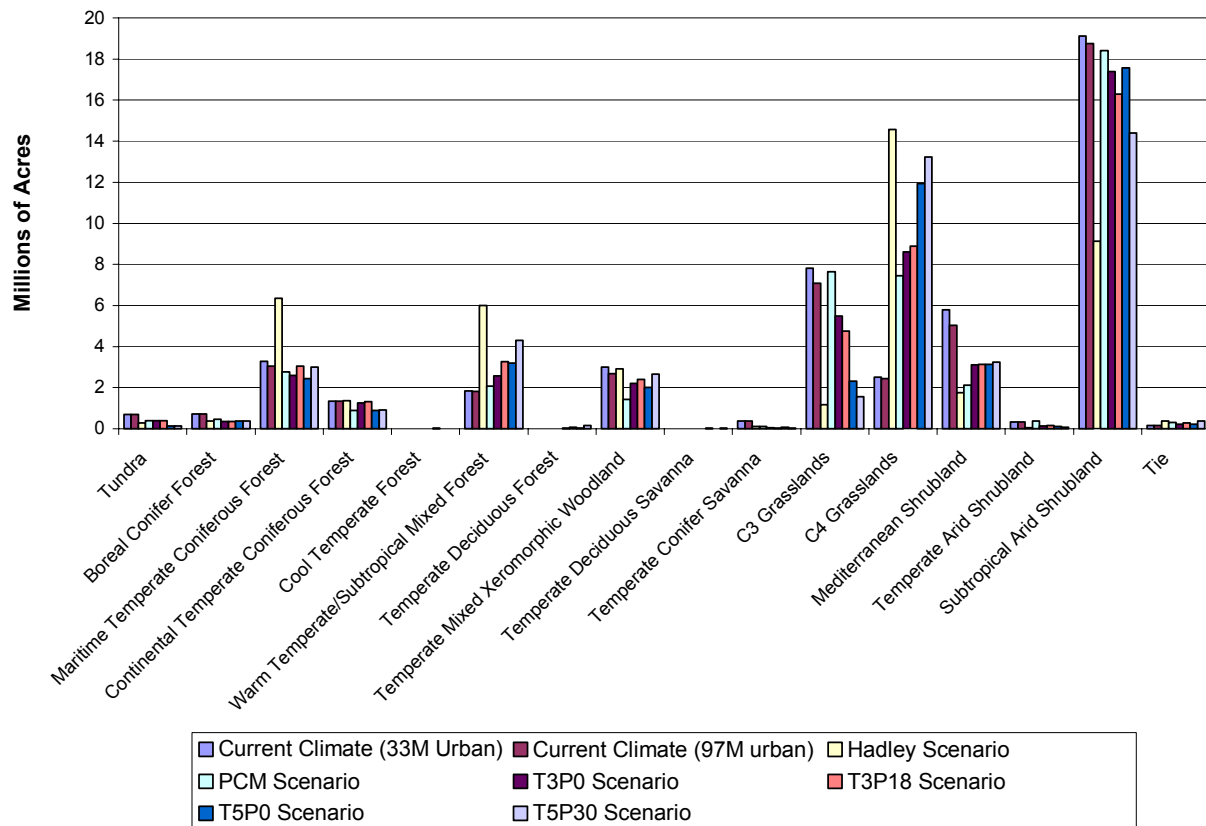


Figure 22. Potential Acreage Of Vegetation Communities For 2100 From Estimated Urbanization Of 92 Million And Climate Change Scenarios As Compared To Current Acreage For Each Community Type

The maps and the chart show that urbanization does slightly reduce the total area covered by most vegetation types. The vegetation types most affected are Mediterranean shrubland (chaparral) and C₃ grassland, but even here the reductions in coverage are only about 15% and 10%, respectively; this occurs primarily in the area from Los Angeles to San Diego. One reason that the losses are modest is that a grid cell is classified as urban only if development covers more than 50% of the cell. Undoubtedly there are many more grid cells in which significant urbanization has occurred but where natural vegetation still occurs over more than 50% of the cell; these losses are not reflected in the maps or the chart.

Climate change has much more dramatic effects on the distribution of vegetation types than does urbanization. For the area covered by this analysis, most vegetation types, including tundra, boreal forest, Mediterranean shrubland, C₃ grassland, and subtropical arid shrubland, are projected to decrease in extent. C₄ grassland and warm temperate/subtropical forest increase under all climate scenarios, and maritime conifer forest benefits under the relatively wet HadCM2 scenario.

California's ecological diversity is apparent both within communities (i.e., the number of species that occur within one community) and at the landscape scale, where large numbers of distinctly different vegetation types can be found in close proximity. Galbraith et al. used the Shannon-Wiener diversity index (Krebs, 1978) to evaluate how this landscape-level diversity might change as a result of urbanization and climate change. The index is sensitive not only to

the number of different vegetation types in a region but also to their evenness in terms of area covered. Areas that have large numbers of vegetation types and where all types are equally prevalent would have the highest diversity indices. Areas with fewer vegetation types or where one or a few dominate would have lower index values

Urbanization has only a minor effect on the landscape diversity index; the effect of climate change in conjunction with urbanization varies depending on the climate scenario (Figure 23). There is essentially no change under the wetter HadCM2 scenario and a modest increase in diversity under the wet 3°C, 18% P scenario. In contrast, the diversity decreases under the other climate change scenarios, with particularly large decreases under the dry PCM and 5°C, 0% P scenarios and even under the warm and wet 5°C, 30% P scenario.

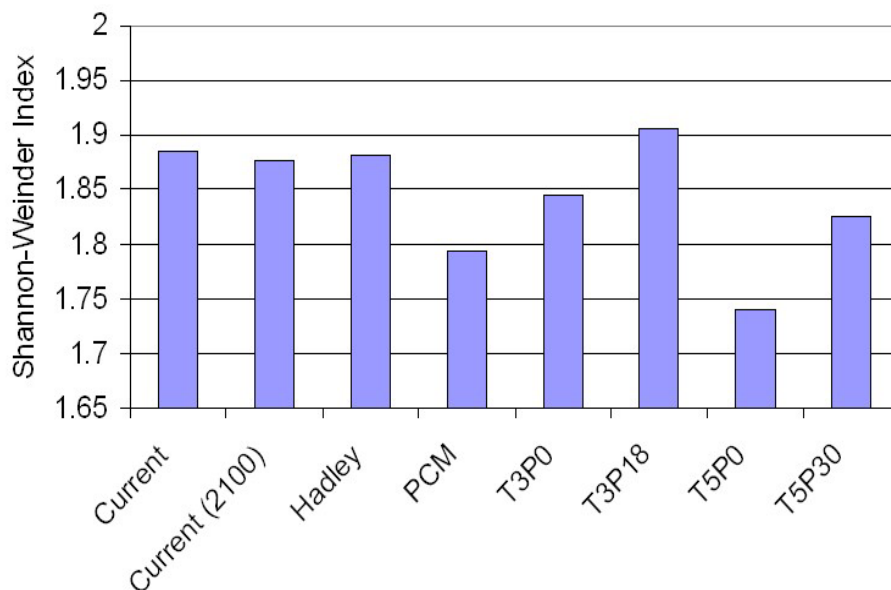


Figure 23. Landscape Diversity As Measured Using The Shannon-Wiener Index Based On The Estimated Changes In Community Type Extents Under Climate Change Scenarios By 2100 And 92 Million Estimated Population

Analysis of coastal sage scrub

Of all the vegetation types studied in this analysis, Mediterranean shrubland proved particularly sensitive to climate change and urbanization. It is projected to decrease in extent within the analysis area by 30% to 60%, depending on which climate scenario is used. The sensitivity of Mediterranean shrubland to both urbanization and climate change is noteworthy because the category is actually composed of several relatively distinct and rarer vegetation or community types, all commonly known as chaparral. One of these is coastal sage scrub, which is found primarily closer to the coast, on sandier soils, and in more xeric sites than other types of chaparral (Keeley and Keeley, 1988). Currently CSS can be found from the central California coast south to northern Baja California. Figure 24 shows the current actual distribution of CSS as determined by the California GAP project (Davis et al., 1998) and the distribution as modeled with MC1 (with the current urbanization and agriculture mask applied).

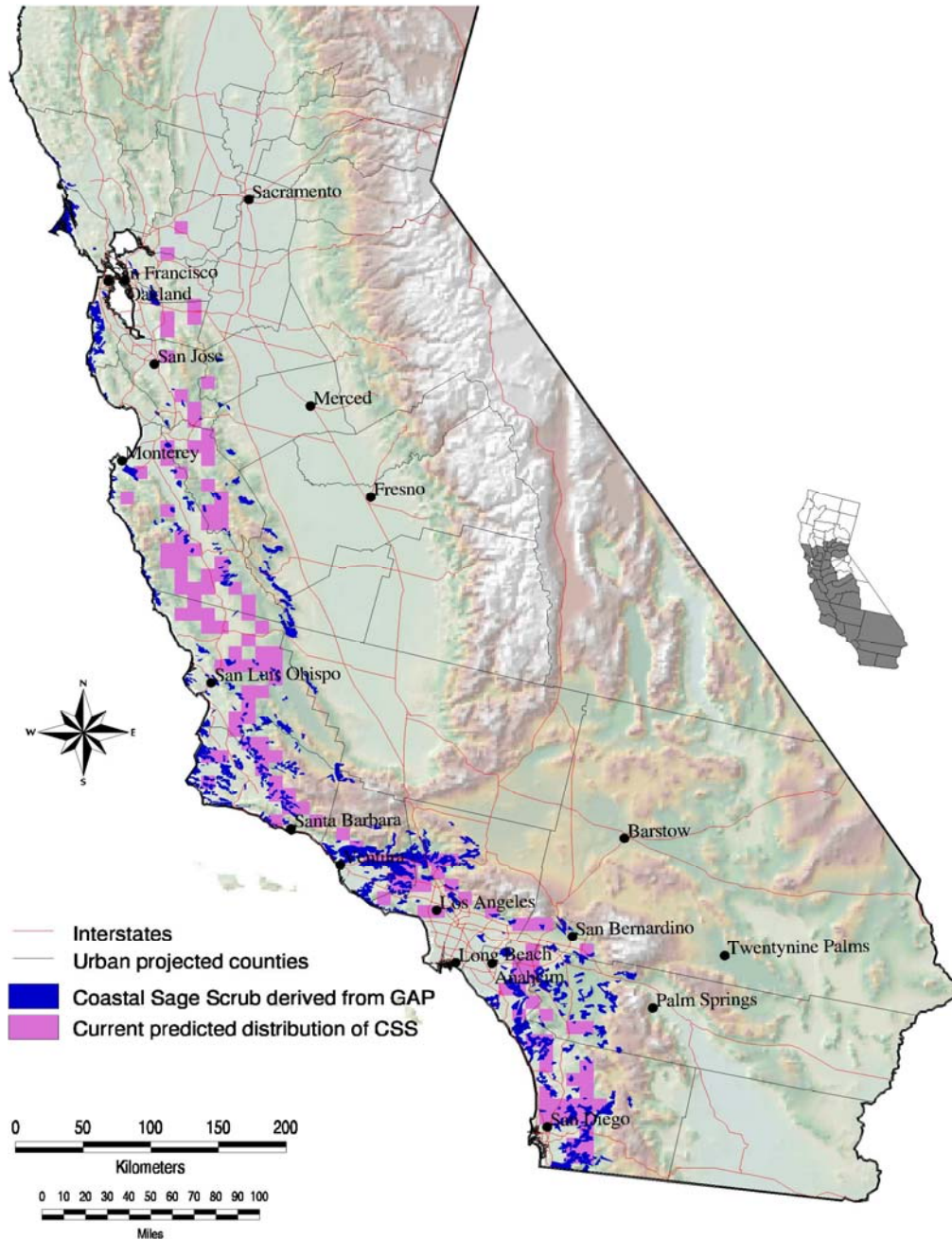


Figure 24. Comparison Of Current Distribution Of CSS As Derived From The GAP Project (Davis Et Al., 1998) At 1 Ha Resolution And Modeled CSS At 100 Km2 Resolution With MC1

CSS is of considerable conservation interest for several reasons. First, its current distribution is highly reduced and fragmented compared with its historical range: since the middle of the 18th century, the extent of CSS has been reduced by approximately 90%, mainly as a result of agricultural, residential, and industrial land conversions. Future losses of CSS resulting from urbanization or climate change will further threaten the integrity and survival of this already rare community type. CSS is home to the California gnatcatcher (*Poliioptila californica*), which the

U.S. Fish and Wildlife Service (USFWS) listed in 1993 as threatened under the Endangered Species Act.

Because of its already threatened status and its likely sensitivity to future urbanization and climate change, the investigators selected CSS for more careful analysis at higher resolution. The distribution of CSS as modeled by MC1 (Figure 24) was determined by assuming that CSS would comprise all Mediterranean shrubland within 100 km of the southern coast, at elevations of less than 700 m, and westward of any topographic barriers. When the distribution of 100 km² grid cells that were classified as CSS (with urban and agricultural areas masked out) is compared with the actual distribution based on the GAP project (Figure 24), it appears that the model does a reasonably good job of predicting where CSS will dominate.

The total area covered by CSS is projected to be reduced by about 20% from urbanization in the 21st century, with most of this reduction occurring in the area between Ventura and the border with Mexico (Figure 25). When climate change is also considered, the effects are far more dramatic, particularly for some of the climate scenarios (Figure 26 and Figure 27, and Figure 28-Figure 31) and in urbanized areas. Although the climate scenarios differ in projecting precisely where CSS will occur, all the scenarios project that it will continue to dominate in areas along the central California coast. It is along the southern coast where the combination of urbanization and climate change poses the most serious threats, and conservation of CSS is already receiving considerable attention in this area. To identify those areas that might provide the most promising sites for maintaining CSS in 2100, only those grid cells that currently are classified as CSS *and* are projected to remain CSS under *all* six of the climate scenarios were identified. Only five of these are in the region between Ventura and the Mexican border, one near Irvine and four east of San Diego (Figure 32). Three of the cells would convert to mostly urban areas under the 92 million population scenario.



Figure 25. Potential Current Distribution Of CSS Under 92 Million Population Scenario

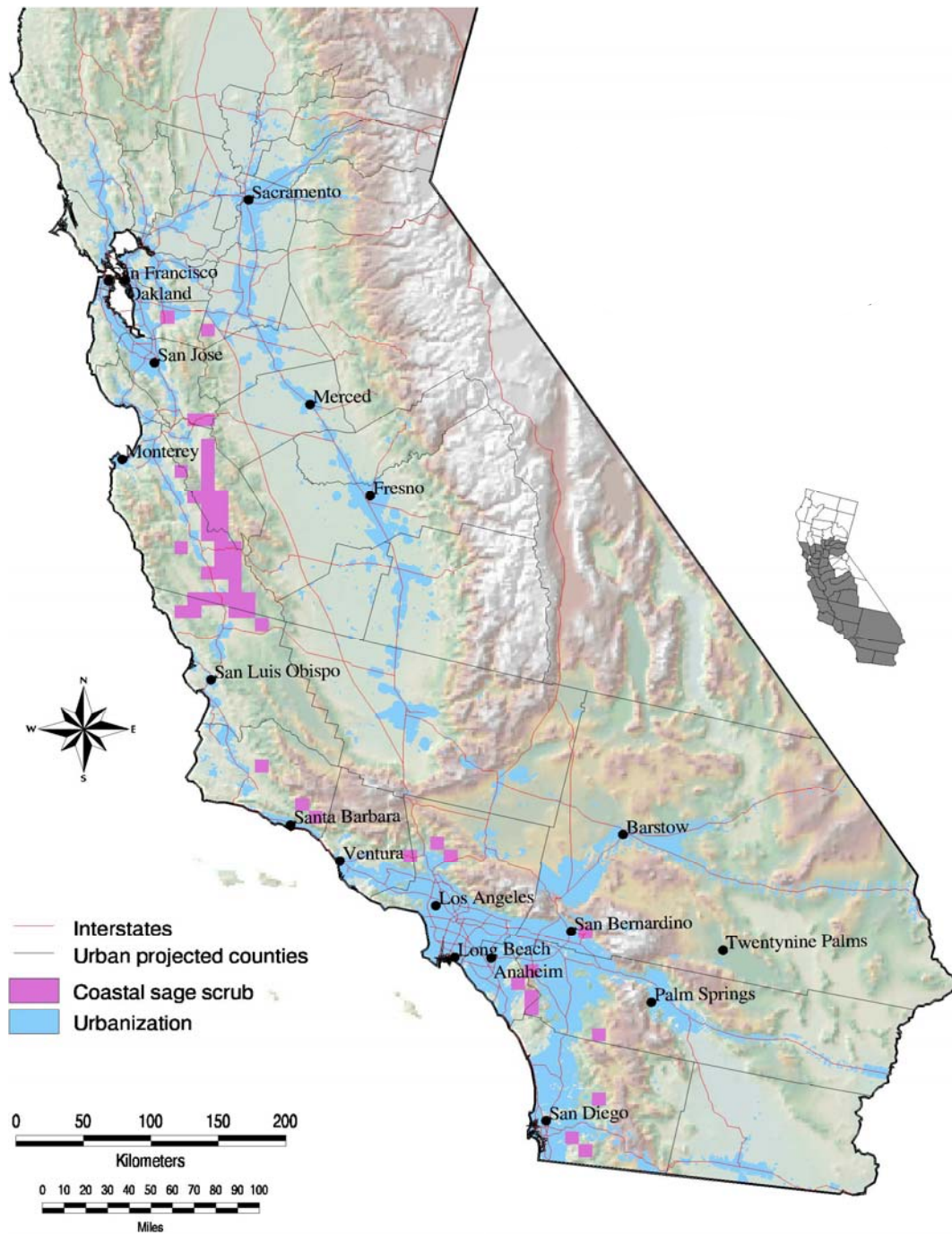


Figure 26. Potential Distribution Of CSS By 2100 Under The Hadcm2 Climate Change Scenario And 92 Million Population

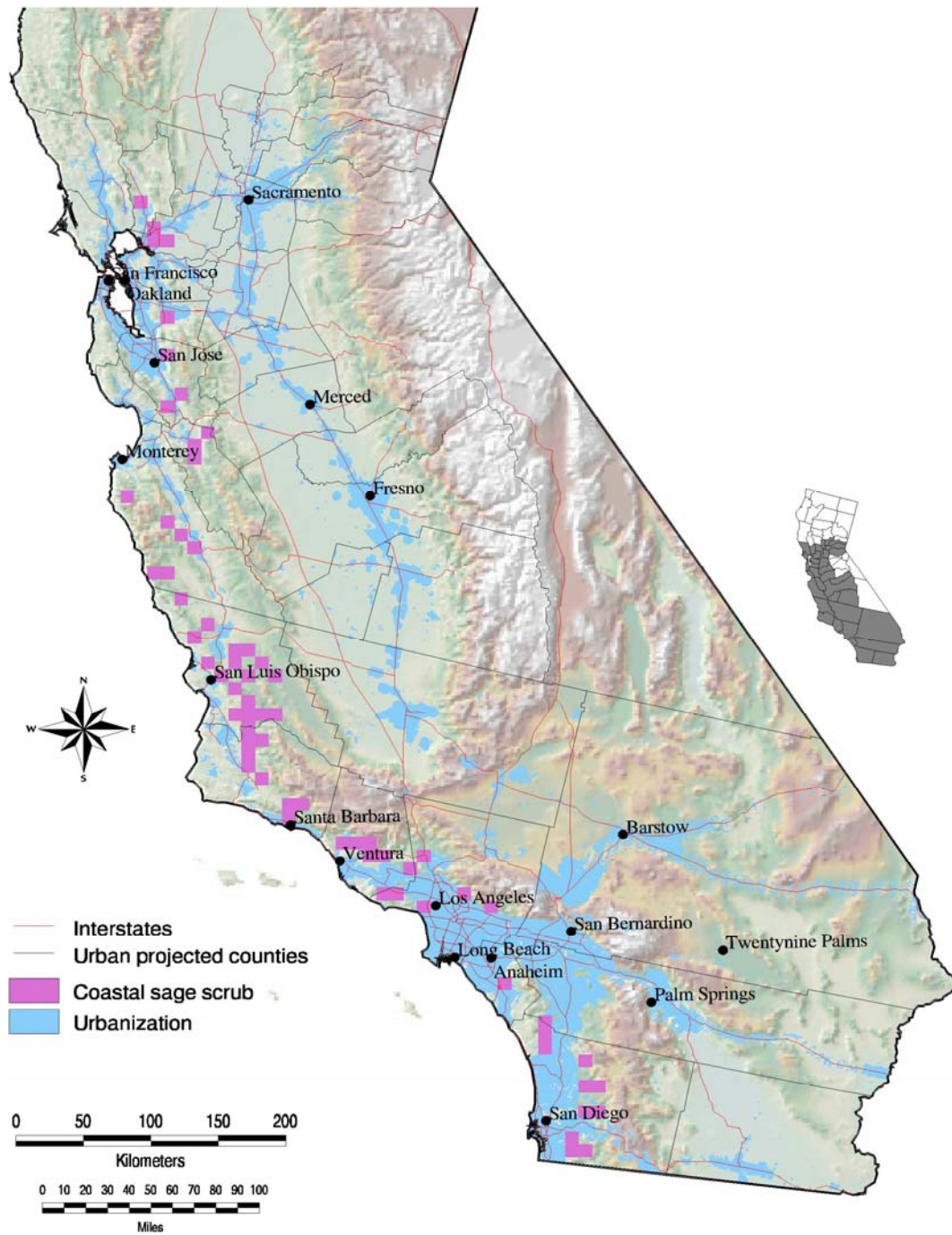


Figure 27. Potential Distribution Of CSS By 2100 Under The PCM Climate Change Scenario And 92 Million Population



Figure 28. Potential Distribution Of CSS By 2100 Under The 3°C, 0% P Climate Change Scenario And 92 Million Population

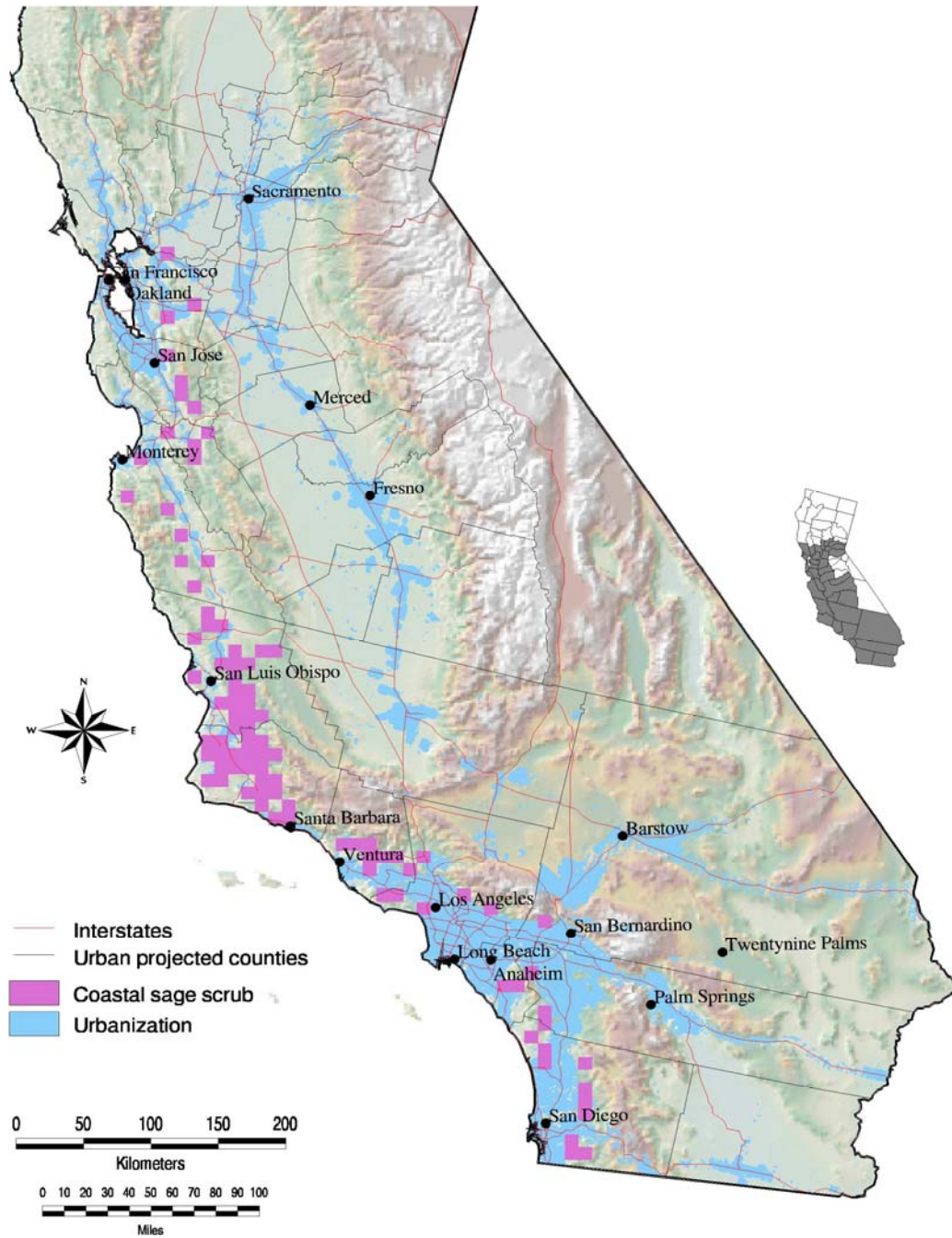


Figure 29. Potential Distribution Of CSS By 2100 Under The 3°C, 18% P Climate Change Scenario And 92 Million Population

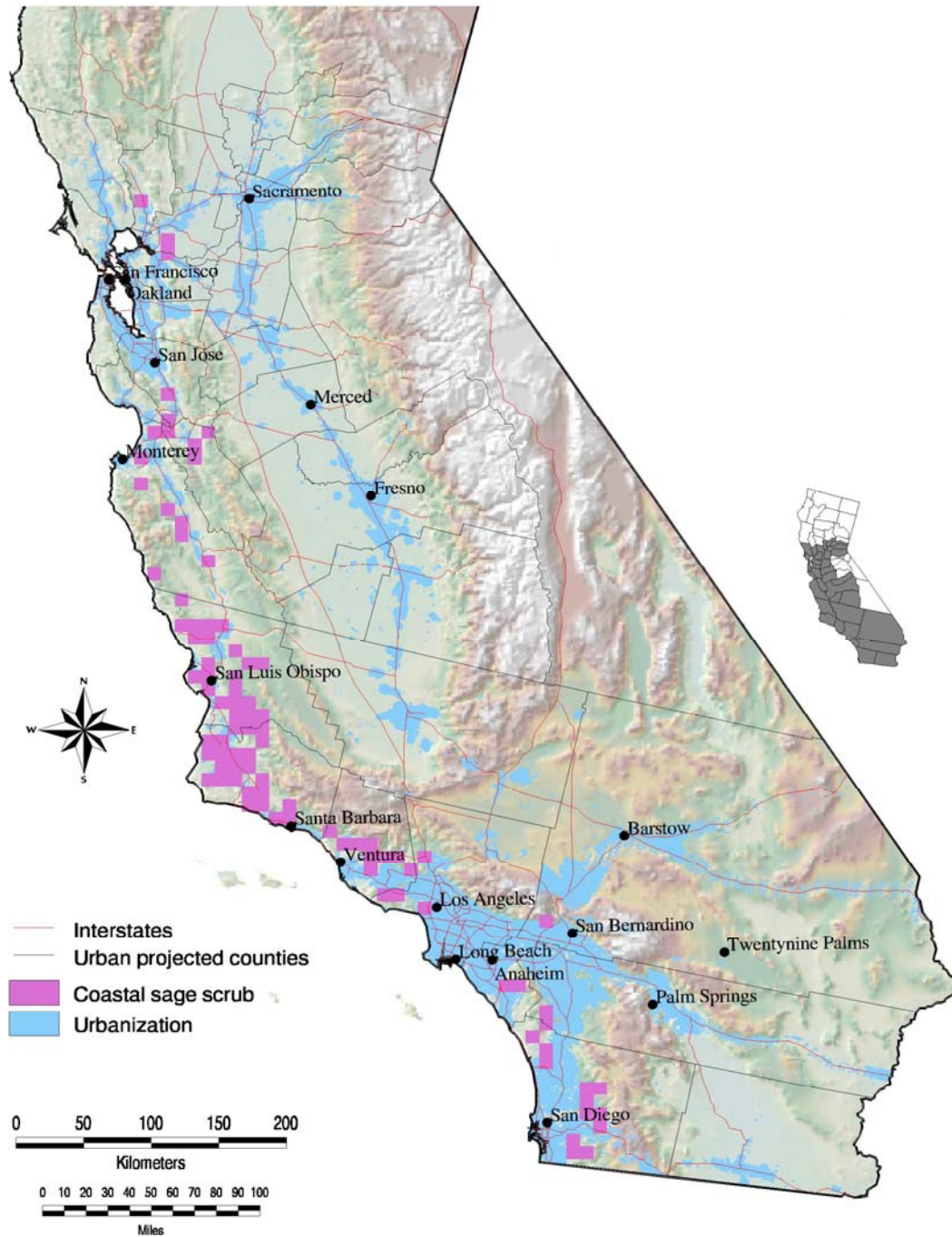


Figure 30. Potential Distribution Of Csx By 2100 Under The 5°C, 0% P Climate Change Scenario And 92 Million Population



Figure 31. Potential Distribution Of CSS By 2100 Under The 5°C, 30% P Climate Change Scenario And 92 Million Population

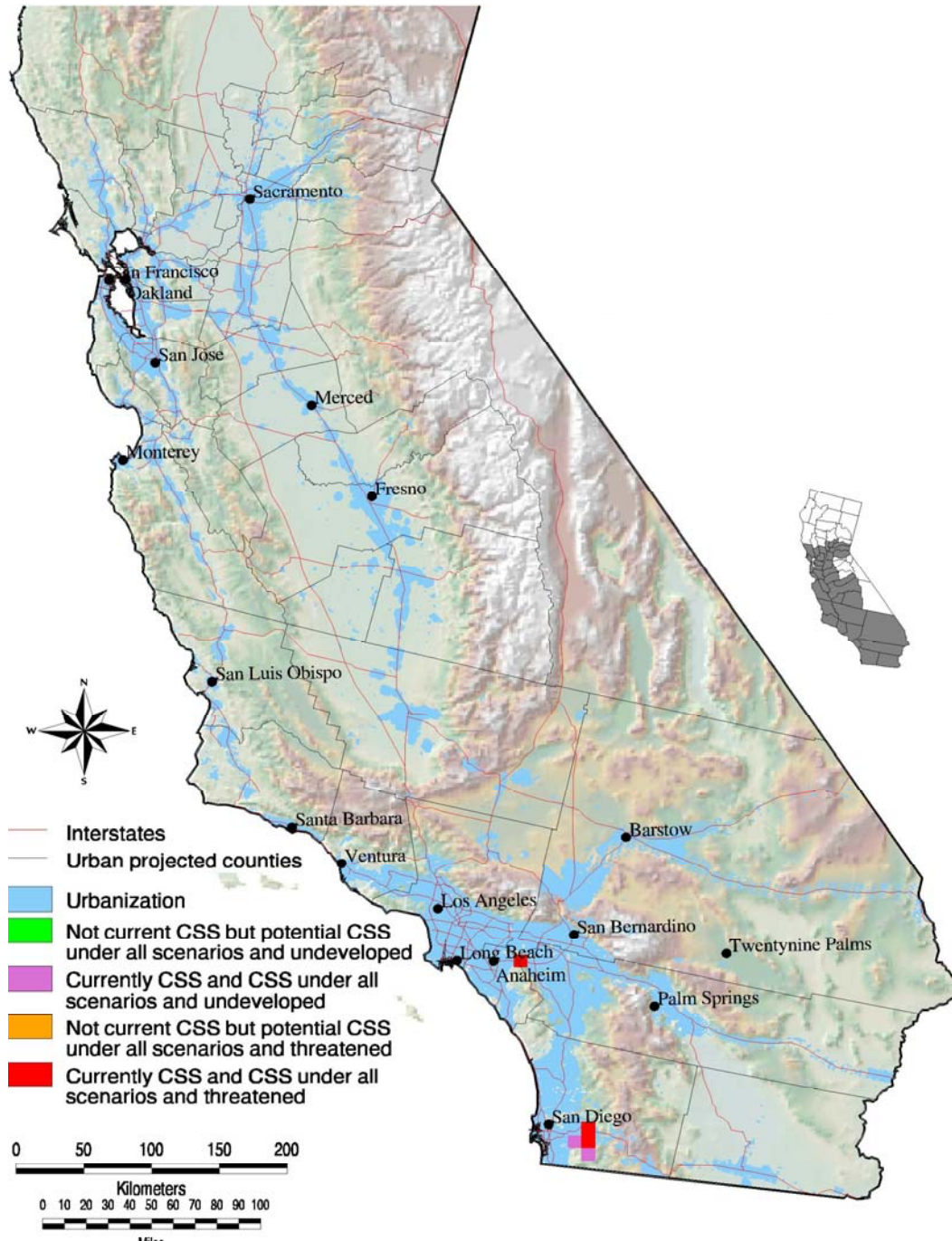


Figure 32. Potential Distribution Of CSS By 2100 Under All Climate Change Scenarios And 92 Million Population Scenario

Galbraith et al. selected the area east of San Diego for the more detailed spatial analysis (Figure 33). The four grid cells were overlaid on the actual distribution of CSS from the GAP project, and on the projected urbanization for 2100 on a 1 ha scale. One of the grid cells currently supports a considerable amount of CSS and is not projected to see any development within its boundaries by 2100. Consequently, it seems to represent a reasonably large area where CSS might persist. The other three grid cells are already partially urbanized and are projected to

experience further development, although only two get classified as urban by the coarser scale approach. Areas of CSS within these three grid cells could be the focus for future conservation efforts, particularly if they include steeper, more mountainous areas where development is less likely.

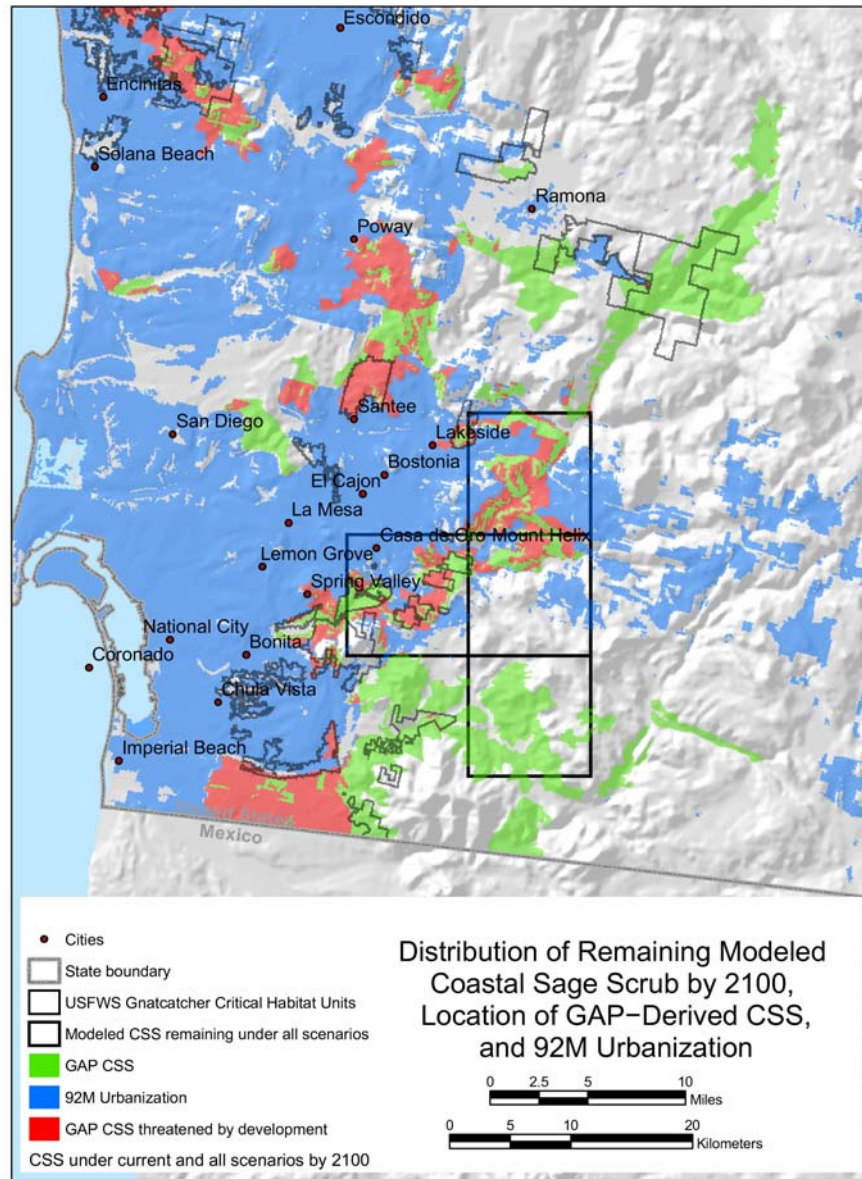


Figure 33. Current Distribution Of GAP-Derived CSS (1 Ha Resolution) In San Diego Region, Estimated Distribution Of 92 Million Urbanization (1 Ha Resolution), And GAP-CSS That Is Threatened By 92 Million Urbanization. . Black boxes outline 10 km² modeled CSS areas that are currently CSS and estimated to remain CSS under all climate change scenarios examined. The figure also indicates areas designated as critical habitat units for the California gnatcatcher by the USFWS (Personal communication, Tony McKinney, GIS Coordinator, USFWS Carlsbad, March 21, 2002).

Limitations

The analysis has a number of limitations:

- Climate change, development, and ecosystem behavior cannot be accurately predicted in the future.
- The vegetation model does not include critical processes such as dispersal and migration, and does not include other important species such as pests, pathogens, and invasive species. Also, the MC1 model projects changes in vegetation types but does not simulate actual species. MC1 does not actually simulate CSS, and that the current and projected future distributions of CSS were based on a few simple rules that might not always apply.
- Urbanization and agriculture are not the only forms of land use change that could affect the distribution and integrity of natural vegetation, especially CSS. Changes in fire regimes, and in grazing and other forms of management, can have more subtle but still significant effects on the composition and functioning of natural ecosystems. Still another anthropogenic threat to natural vegetation is exotic, invasive species, which, especially in areas already disturbed by grazing or other activities, can out-compete native species.
- Just because a grid cell is projected to become urban or no longer climatically suitable for a particular vegetation type does not mean the vegetation will not be found there. Because of the physical and ecological heterogeneity within most grid cells, in many locations it is likely that many of the existing vegetation types will be able to persist after climate changes, simply by migrating locally to a different microsite instead of migrating

to some distant location in another grid cell. The most dominant vegetation type may change, resulting in the grid cell being classified differently, but much or most of the original diversity may persist. And cells that are classified as urban may still contain natural vegetation.

The results from this analysis are indicative of the sensitivity of the modeled systems to the multiple stresses imposed by climate change and land use change.

Timber

For the study on the impacts of climate change on the California timber industry (Appendix XII), Mendelsohn combined the estimated change in location and productivity of California vegetation described in the ecosystem section with a timber production model. Because the California timber industry relies mostly on softwoods, the timber study focused on softwood timber production. The analysis focused on privately owned timberland because harvesting from public lands for timber production is a very small share of the commercial timber market (California Department of Forestry and Fire Protection, 2001). The softwood forests currently exist only in central and northern California.

The study relied on the dynamic predictions of the ecological model to estimate forest productivity and forest area each decade. Net primary productivity (NPP) and total above-ground carbon estimates from the ecosystem study were used to estimate change in yield in the timber analysis.

An important prediction from the ecosystem study is that the area of softwoods is estimated to decline with warming. By the end of the century, this loss in area outweighs the increase in productivity, suggesting that the total supply in California will fall. Net (undiscounted) revenues are estimated to increase slightly in the early part of the century and decrease toward the end of the century under the incremental scenarios. Under the GCM scenarios, net (undiscounted) revenues rise slightly throughout the century.

At first, the productivity effect dominates because it changes growth rates in all existing trees. Using total carbon in forests, increases in annual timber revenue in 2020 range from \$15 million in the HadCM2 scenario using NPP to \$32 million in the +5°C, +30% precipitation scenario. By the end of the century, the gradual reduction in softwood area dominates and the supply tends to fall. By 2100, the changes in revenue are estimated to range from -\$159 million in the +5°C, 0% precipitation scenario to +\$109 million using the HadCM2 scenario and NPP. In all cases, the present value of timber revenues (i.e., discounted revenues) is positive. We see this result because longer term losses have smaller present values relative to nearer term gains. The benefit from warming ranges from \$161 million (0.1%) in the 3°C, 0% precipitation scenario with carbon to \$1.2 billion (6.3%) in the PCM scenario using NPP. All regions have increased timber revenues (in present value) except for the Central Valley.

The analysis assumes that prices for wood products will not change. Should global timber supply increase, prices would fall. Estimations of climate change effects on the global timber industry project increases in global productivity and resulting declines in timber prices (Gitay et al., 2001; Sohngen et al., 2001). If global timber prices decline, California producers are estimated to lose income because the price effects would dominate the small changes in productivity in California. The producers would lose income even under the GCM scenarios that estimated increased productivity. The estimated losses to producers from the net effect of climate change (including change in global prices and productivity in California) range from \$116 million per year in the HadCM2 scenario with NPP to \$315 million in 2100 with the +5°C, 0% precipitation with carbon scenario. Throughout the century, the present value of total damages ranges from \$0.6 billion to \$1.4 billion. Impacts to timber producers appear to be more sensitive to changes in global prices from global effects than to the direct effects of climate change in California.

On the other hand, if global prices decline, California consumers would gain because wood products would become less expensive. This study estimates that the benefits to consumers would be much larger than the losses to producers. Indeed, the gain in consumer surplus (the difference between what consumers are willing to pay for goods and the market price) is estimated to be approximately \$500 million in 2020 and \$1.0 to \$1.5 billion in 2100. The net present value would be \$13 billion to \$14 billion because of the price drop resulting from increased global supply. On the whole, the state gains from the drop in timber prices because California consumes far more timber than it produces (California Department of Forestry and Fire Protection, undated). The state is a net importer of timber, which means that price effects on consumers will outweigh the corresponding price effects on producers.

3.2. Water Resources and Agriculture

3.2.1. Introduction

California was able to rapidly expand its population and economy in the 20th century to a large degree because of society's ability to transport water long distances. Most of the water in

California is used far from where it falls as precipitation. It is mainly collected in the Sierra Nevada⁴ and transported to the valleys and farther south. The water is used mainly for irrigation for agriculture (which withdraws about 80% of water supplies; U.S. Geological Survey [USGS], 1995), but also for municipal and industrial consumption, hydropower, and thermopower. Without this water, it is unlikely that such extensive development would have taken place.

California has the most productive agricultural system in the country, a level of production that would not be possible without the availability of water for irrigation. Almost all agricultural land in the state is irrigated. Because agriculture consumes most of the water in California, the state's water resource management and agricultural systems are closely tied. The effects of climate change on agriculture and water resources must be considered together because changes in water supplies can limit or expand agricultural production and changes in demand for irrigation can stress or ease the allocation of the state's water supply.

To assess the potential effects of climate change on California's water and agriculture systems, the investigators first estimated the direct effects of climate change on runoff (Appendix VIII) and crop yields (Appendix IX). Change in runoff is used to examine impacts on water supplies (Appendix VII), and changes in crop yields and irrigation demand are used to estimate potential agricultural production and water demand (Appendix X). Changes in water resources and agricultural production are modeled simultaneously to account for interactive effects among crop yield, demand for irrigation, and water supply.

The water and the agricultural analyses were conducted with the goal of providing useful input to the next California Department of Water Resources state water plan.

3.2.2. Runoff

The goal of the runoff study by Miller (Appendix VIII) was to examine how climate change might affect a representative set of rivers in California. This information was spatially extrapolated for use in the water management study (Appendix VII). Miller selected six California basins: Smith River, Sacramento River, Feather River, American River, Merced River, and Kings River (see Figure 34). These basins were chosen because they cover a wide geographic and elevation range, and are representative of the basins used for water supplies in California (excluding the Colorado River).⁵ The study used the Sacramento Soil Moisture Accounting Model and the Anderson Snow Model to estimate changes in snowpack, snowmelt, and runoff.

4. About 10% of the state's water comes from the Colorado River.

5. Analysis of change in the Colorado River was based on previous studies (e.g., Mendelsohn and Neumann, 1999).



Figure 34. Location Of The Six Study Basins (Smith At Jed Smith, Sacramento At Delta, Feather At Oroville Dam, North Fork American At North Fork Dam, Merced At Pohono Bridge, And Kings At Pine Flat)

Increased temperatures and changes in precipitation are key factors affecting the snowpack and timing of runoff from each basin. Basin elevation is also critical because high elevation areas can maintain or even increase snowpack.

Snowpack declines in most of the basins modeled because more precipitation falls as rain under the climate change scenarios (Figure 35) and because higher temperatures result in more melting (Figure 36). The relationship is more complex in higher elevation basins such as the Kings and Merced. In upper portions of these basins, temperatures stay below freezing in the winter and spring. Increased precipitation in these upper reaches is likely to result in a larger snowpack accumulations. Although higher temperatures increase snowmelt, the snowpack can be increased if winter precipitation increases sufficiently in upper basin regions that remain below freezing.

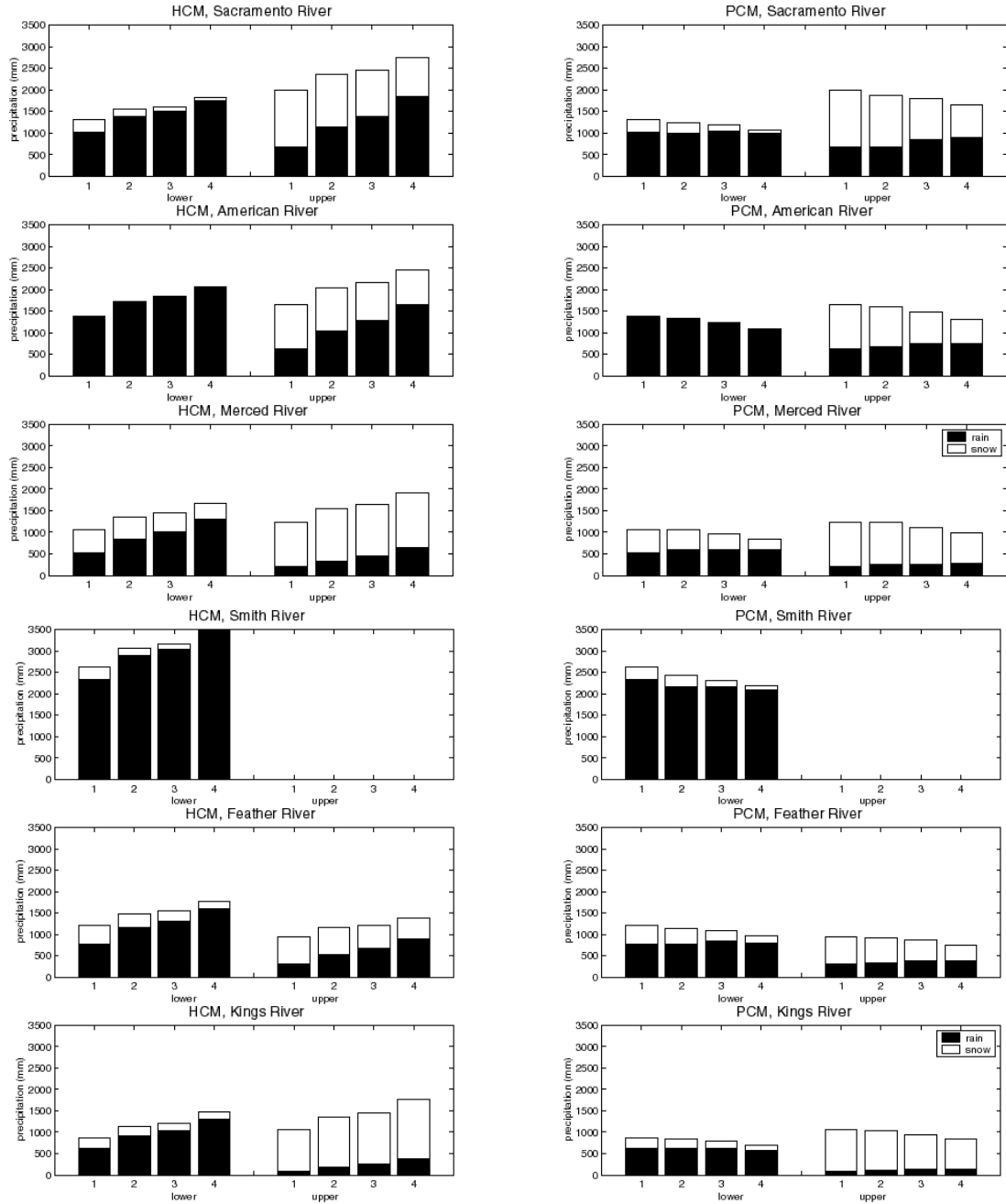


Figure 35. Snow (Clear) And Rain (Solid) Mean Annual Depth For The Lower And Upper Subbasins For Each Climate (1) Baseline, (2) 2010-2025, (3) 2050-2079, And (4) 2080-2099 (HCM Is Hadcm2 Model)

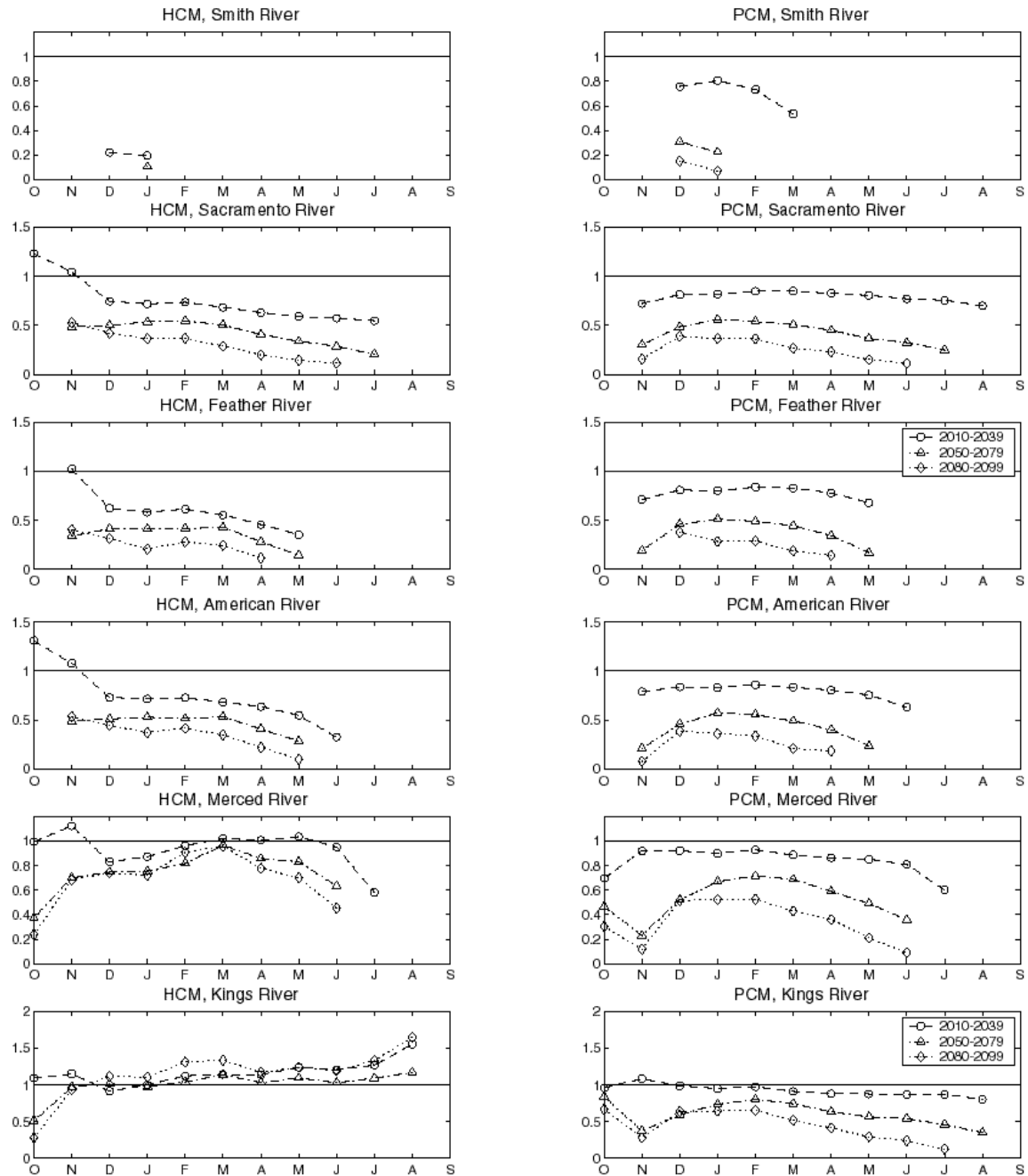


Figure 36. Ratio Of Climate Change To Baseline Mean-Monthly Snow Water Equivalent (SWE) For Each Basin (HCM Is Hadcm2 Model)

Higher temperatures result in an earlier peak in melting of snow (Figure 37), increased snowmelt in winter months, and decreased snowmelt in spring and summer months (because snowpacks have diminished). This varies by basin and scenario, with some basins, particularly lower elevation ones such as American, showing decreased snowmelt throughout most of the year. Higher elevation basins, on the other hand, could have increased snowmelt through most of the year if precipitation increases.

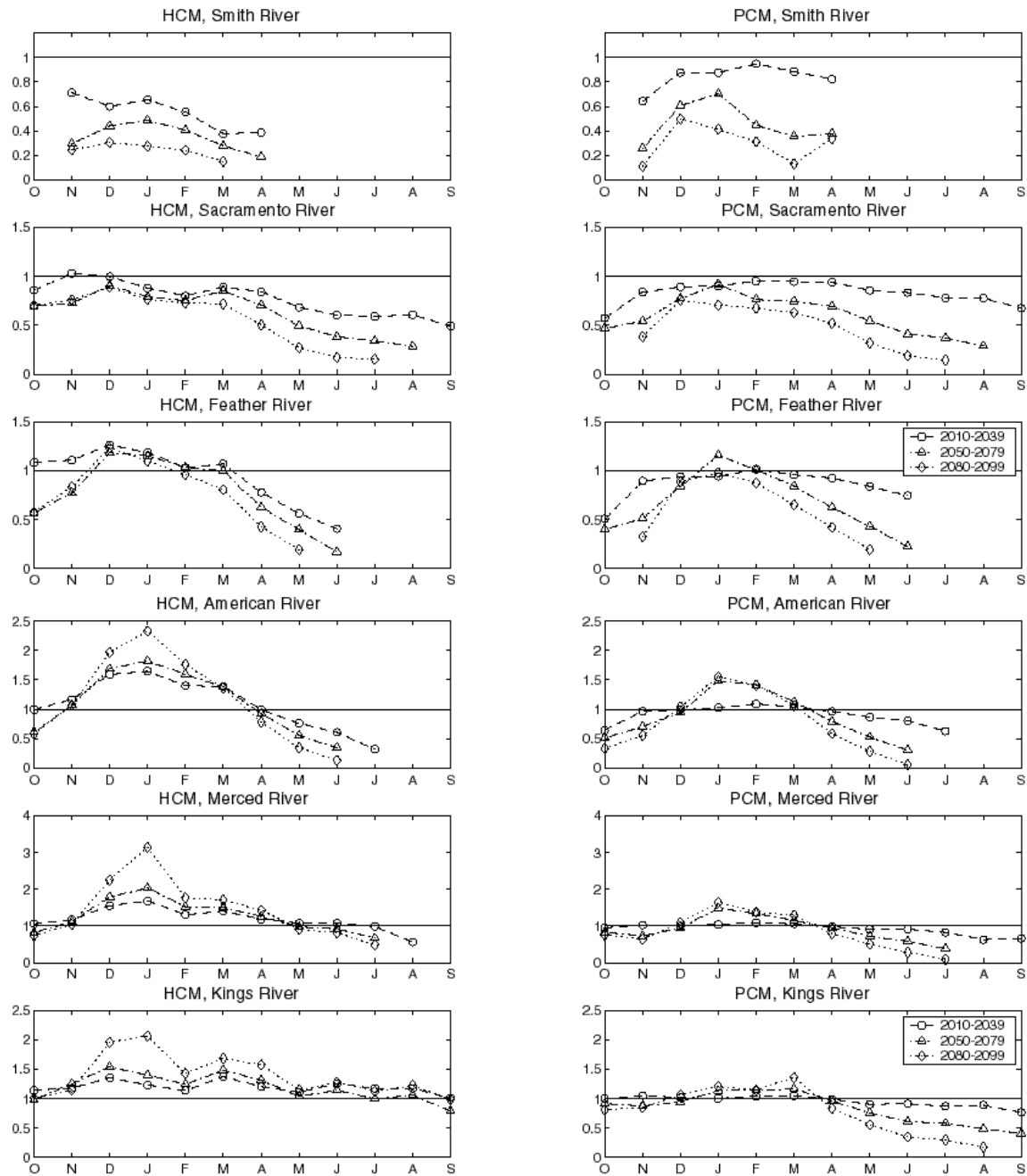


Figure 37. Ratio Of Climate Change To Baseline Mean-Monthly Snowmelt For Each Basin (HCM Is Hadcm2 Model)

The higher temperatures generally result in a shift in peak streamflow earlier in the year (Figure 38 and Figure 39) because of earlier snowmelt. However, the shift is more pronounced in higher elevation basins than in those at lower elevations. Changes in the timing of peak snowmelt can also be affected by changes in the seasonality of precipitation.

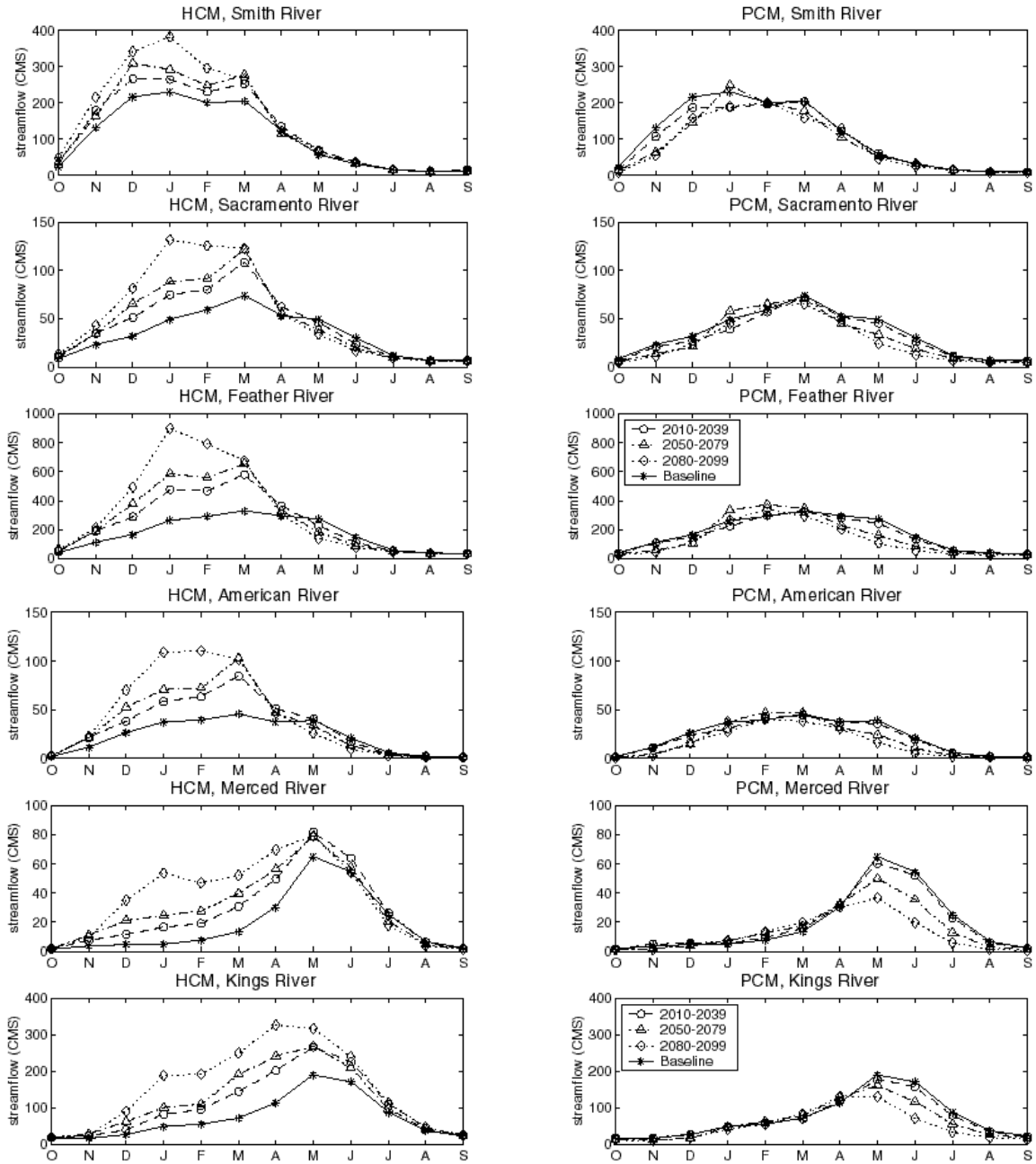


Figure 38. Average Monthly Streamflow Based On The Hadcm2 And The PCM (HCM Is Hadcm2 Model)

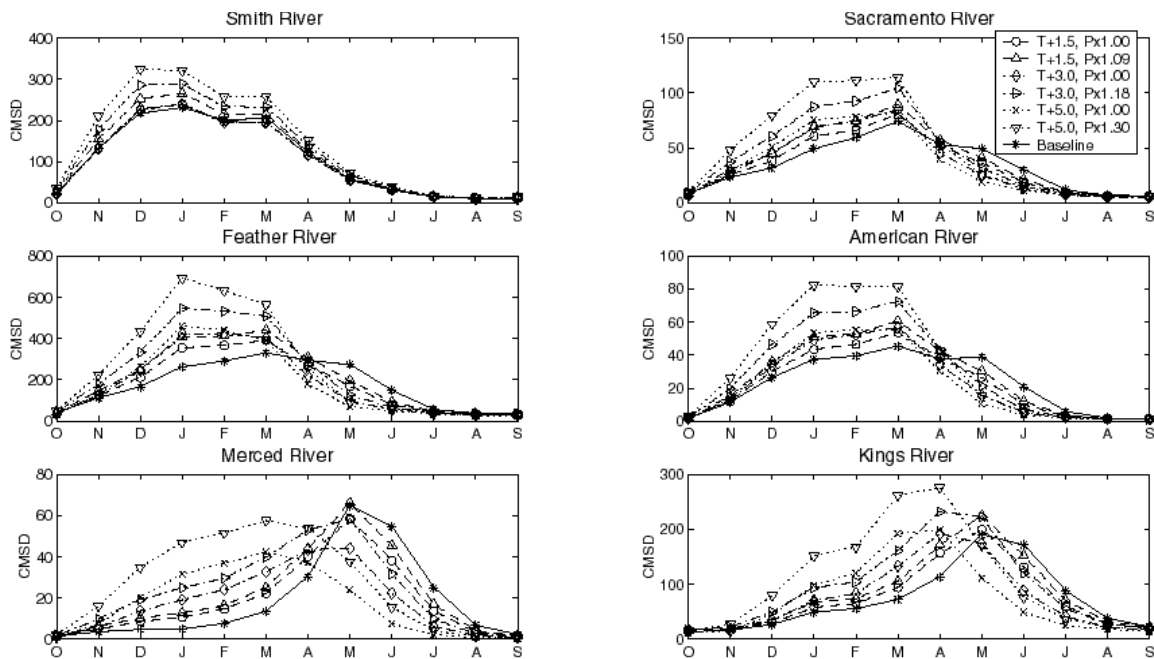


Figure 39. Average Monthly Streamflow Based On The Specified Incremental Changes

Whether the annual volume of streamflow increases or decreases appears to be mainly a function of precipitation. If precipitation rises as in the HadCM2 scenario, annual runoff generally increases. If precipitation declines as in the PCM scenario, so does annual runoff. Changes in seasonal runoff are more complex. Runoff during spring and summer is lower in all basins under all the scenarios except HadCM2, in which case it is unchanged. Runoff in the fall and particularly in the winter and early spring is higher in most basins under most scenarios because higher temperatures cause the snow to melt earlier. Fall and winter runoff increases most under the wet HadCM2 scenario, but it changes only slightly under the dry PCM scenario.

Flood potential in California snowmelt river basins is estimated to increase under all scenarios of climate change, wet or dry (Figure 40 and 28), mainly because the peak daily flows happen earlier in the year, and the percentage of precipitation as rain will have significantly increased. The increases in peak daily flows are estimated even under scenarios that assume no change in precipitation (the incremental scenarios) and the PCM scenario, which shows reduced precipitation. The increase in peak flow is most pronounced under all scenarios in high elevation basins such as Merced. If precipitation increases, volume during peak runoff increases more. For example, under the HadCM2 scenario, the volume of flow during the highest flow days could more than double by the end of the 21st century in the six basins studied. This could result in substantial increase in flood risks in such flood-prone areas as Sacramento. Because temperature is the main driver of increased peak runoff, not precipitation, this outcome is highly likely to be a result of climate change. If climate change leads to not only an increase in average precipitation but also a shift to more extreme precipitation (see Karl and Knight, 1998), then peak flows could increase even more.

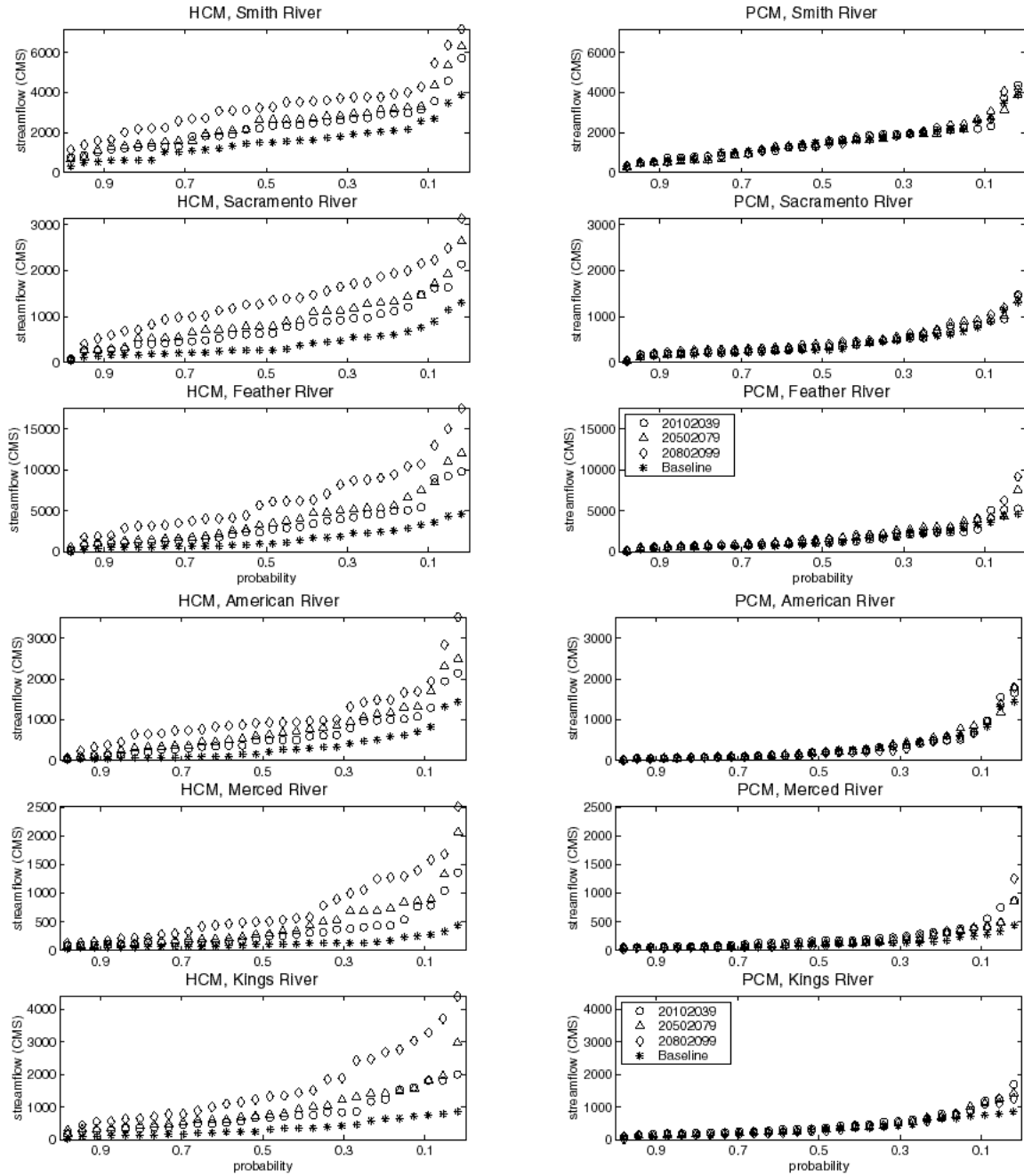


Figure 40. Exceedence Probabilities Of The Peak Daily Flow For Each Year For Each Climate Change Scenario (HCM Is Hadcm2 Model)

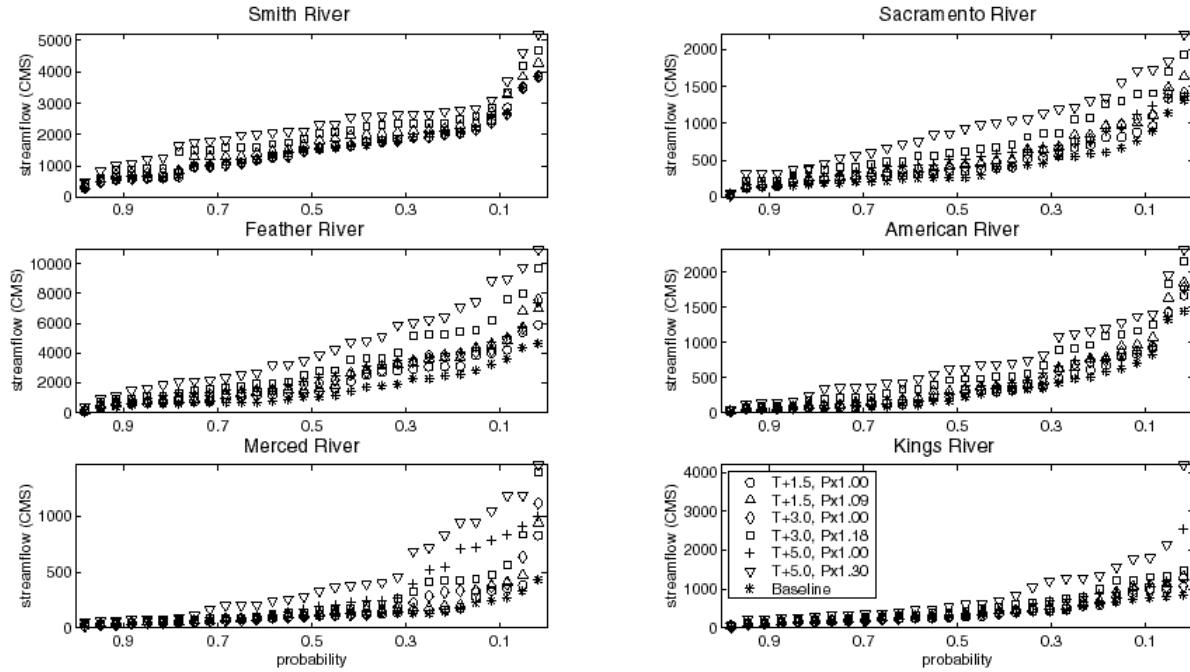


Figure 41. Exceedence probabilities of the peak daily flow for the specified temperature and precipitation incremental climate change

3.2.3. Water Resources

For this study (Appendix VII), Lund et al. used CALVIN, a model of the entire California water management and delivery system. The CALVIN model explicitly integrates the operation of water facilities, resources, and demands for California's vast intertied system. It is the first model of California water that manages surface waters, groundwater, and water demand simultaneously across the state. CALVIN covers 92% of California's population and 88% of its irrigated acreage (Figure 42). With roughly 1,200 spatial elements, the model examines 51 surface reservoirs, 28 groundwater basins, 18 urban demand areas, 24 agricultural demand areas, 39 environmental flow locations, 113 surface and groundwater inflows, and numerous conveyance and other links — all of which represent the size and complexity of California's water management infrastructure (University of California at Davis, 2003).

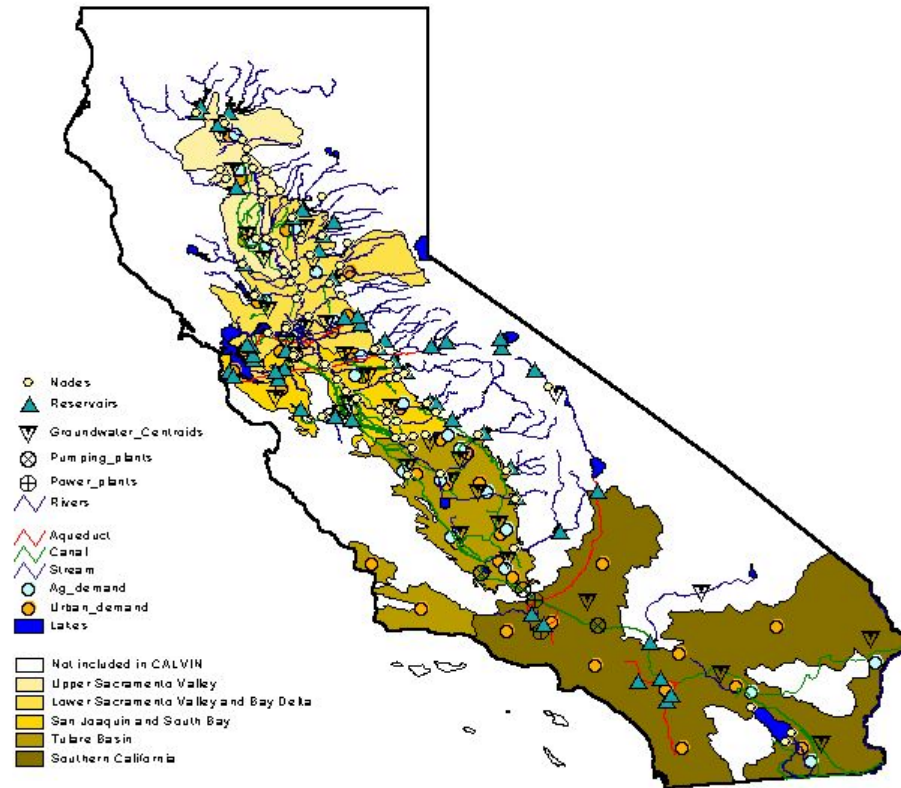


Figure 42 .Water Demand Areas And Major Inflows And Facilities Represented In CALVIN

A key aspect of using the CALVIN model for this study is that it is an engineering “optimization” model driven by economics. The model, unless otherwise constrained (e.g., to simulate current water allocation rules), operates facilities and allocates water to maximize statewide agricultural and urban economic value from water use. CALVIN accounts for different types and locations of demands for water (see Figure 42). Essentially, the model finds the “best” water operations and allocations for maximizing regional or statewide economic benefits. This pursuit of economic objectives is initially limited by water availability, facility capacity, and environmental and flood control restrictions. Lund et al. tested two cases for 2020. One involved continuing current rules and regulations, and the other involved allocating water supplies based on free market conditions. They assumed free market conditions for the 2100 runs, assuming population growth and no climate change, and population growth and climate change. This is because it would be infeasible to assume that current operating constraints continue to 2100.

As inputs, CALVIN uses estimates of changes in runoff from mountains (“mountain rim inflow”), which account for 72% of supplies, local accretions to surface water (11%), and groundwater recharge (17%). The model also accounts for evaporation from reservoirs, which currently reduces supplies by 4%. The researchers used the runoff estimates of the six index basins in the runoff study (Appendix VIII) to develop runoff estimates for each of 37 major surface inflows to California’s water supply system in CALVIN. Next, streamflow changes for each of the six index basins were mapped to the 37 major surface inflows to the system, perturbing the 1921-1993 historical flow record to represent historical spatial and temporal

variability of inflows given a generally warmer (and for some scenarios, wetter or drier) climate. Finally, the climate used in for each climate warming scenario model run was used to estimate changes in flows for local runoff, rain-fed deep percolation to groundwater, and reservoir evaporation. The effects of sea level rise were not considered, though they could have important implications for salinity in the Sacramento-San Joaquin Delta.

This study first examined the effects of population and economic growth on water demand. Under a scenario of 92 million Californians by 2100, Table 9 shows a reduction in agricultural acreage, along with about a 10% reduction in water used for irrigation (about 2.7 MAF/year). This is mainly the result of conversion of agricultural land to urban land. In contrast, water for urban uses is projected to increase by two-thirds (about 7.2 MAF /year). CALVIN also projected additional urban water conservation (~1 MAF/yr), newer water reuse treatment (~1.5 MAF/yr) and sea water desalination technologies (~0.2 MAF/yr), increased conjunctive use of groundwater and surface water, and urbanization of agricultural land.

Table 9. Land And Applied Water Demands For California's Intertied Water System (Millions Of Acres And Millions Of Acre-Ft [MAF]/Year)

Land And Applied Water Demands For California's Intertied Water System (Millions Of Acres And Millions Of Acre-Ft [MAF]/Year)						
Use	2020 Land	2100 Land	2020-2100 Change	2020 Water	2100 Water	2020-2100 Change
Urban				11.4	18.6	+7.2
Agricultural	9.2	8.4	-0.75	27.8	25.1	-2.7
Environmental	-	-	-	-	-	-
Total	-	-	-	39.9	44.5	+4.5

Table 10 and Figure 43 present changes in the mountain rim inflow as a consequence of the climate change scenarios. The PCM scenario results in up to a 26% reduction in runoff from the mountains; the HadCM2 scenario results in increases up to 77%. The incremental scenarios fall between these outcomes, ranging from virtually no change to increases up to 28%. Figure 43 indicates that although runoff could increase substantially in winter months, it would be significantly reduced in spring and summer months.

Table 10. Overall Rim Inflow Quantities And Changes

Overall Rim Inflow Quantities And Changes						
Climate scenario	Annual		October-March		April-September	
	Quantity (MAF)	Change (%)	Quantity (MAF)	Change (%)	Quantity (MAF)	Change (%)
1) 1.5°C, 0% P	28.6	1.1	16.4	15.6	12.2	-13.4
2) 1.5°C, 9% P	32.4	14.6	18.7	31.7	13.7	-2.7
3) 3.0°C, 0% P	28.5	0.9	18.2	28.0	10.3	-26.5
4) 3.0°C, 18% P	36.2	28.1	23.3	64.4	12.8	-8.7
5) 5.0°C, 0% P	27.9	-1.1	19.5	37.1	8.5	-39.7
6) 5.0°C, 30% P	40.6	43.7	28.9	103.8	11.7	-17.0
7) HCM 2010-2039	38.5	36.4	22.0	54.9	16.5	17.6
8) HCM 2050-2079	41.3	46.4	25.8	82.0	15.5	10.4
9) HCM 2080-2099	49.8	76.5	33.3	134.3	16.6	18.1
10) PCM 2010-2039	26.5	-6.2	13.2	-6.7	13.2	-5.7
11) PCM 2050-2079	24.4	-13.6	13.7	-3.8	10.7	-23.5
12) PCM 2080-2099	21.1	-25.5	12.2	-14.2	8.9	-36.9
Historical (1922-1993)	28.2	0.0	14.2	0.0	14.0	0.0

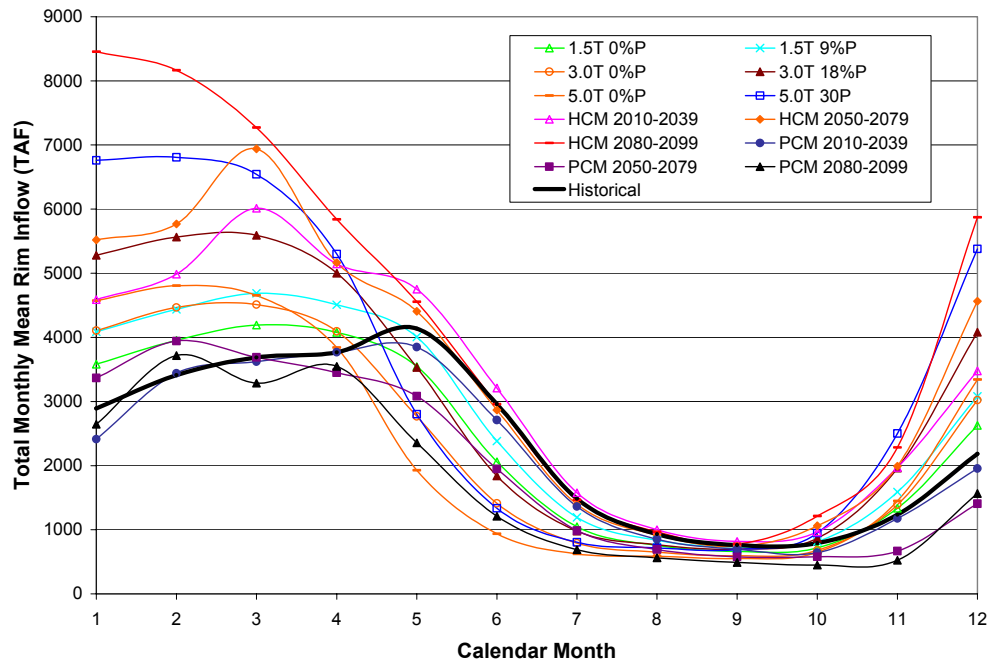


Figure 43. CALVIN 72-Year Monthly Mean Rim Inflows For The 12 Climate Scenarios And Historical Data

Changes in local surface water accretion and groundwater recharge have the same sign as the changes to mountain runoff. Under the GCM scenarios, reservoir evaporation increases by about 22%. The increases in evaporation under incremental scenarios range from 12% (for a 1.5°C increase with a 9% increase in precipitation) to 41% (for a 5°C increase with no change in precipitation).

Table 11 displays changes in raw water availability. Lund and colleagues assumed that no increases in winter runoff would be captured (because of the need to operate reservoirs for flood control) and that all reductions in spring and dry season inflows would be lost for water supplies. However, increases in wet season inflows to groundwater are assumed to be available for water supply. The changes in raw water availability are generally more negative than the changes in mountain runoff. The HadCM2 scenario results in smaller percentage increases in total raw water availability than estimated increased runoff. Although the incremental scenarios show virtually no change to an increase in mountain runoff, the change in water availability ranges from no change to negative. The changes in raw water availability under the PCM scenario are of a similar magnitude as the changes in mountain runoff. In addition, Lund et al. assumed no change in water supply from the Colorado Aqueduct, consistent with California's senior water rights on the Colorado River. To be sure, runoff in the Colorado River is also quite sensitive to climate change (Gleick and Chalecki, 1999).

Table 11. Raw Water Availability Estimates And Changes (Without Operational Adaptation, In MAF/Year)

Raw Water Availability Estimates And Changes (Without Operational Adaptation, In MAF/Year)		
Climate scenario	Average annual water availability	
	Volume (MAF)	Change (MAF, %)
1) 1.5°C, 0% P	35.7	-2.1 (-5.5)
2) 1.5°C, 9% P	37.7	-0.1 (-0.4)
3) 3.0°C, 0% P	33.7	-4.1 (-10.9)
4) 3.0°C, 18% P	37.1	-0.8 (-2.0)
5) 5.0°C, 0% P	31.6	-6.2 (-16.5)
6) 5.0°C, 30% P	36.2	-1.6 (-4.3)
7) HCM 2010-2039	41.9	4.1 (10.8)
8) HCM 2050-2079	40.5	2.7 (7.2)
9) HCM 2080-2099	42.4	4.6 (12.1)
10) PCM 2010-2039	35.7	-2.1 (-5.6)
11) PCM 2050-2079	32.9	-4.9 (-13.0)
12) PCM 2080-2099	28.5	-9.4 (-24.8)
Historical (1922-1993)	37.8	0.0 (0.0%)

For this study, the investigators enhanced the CALVIN model by adding hydroelectric water demands and water storage to the system. Hydroelectric demands have played a significant role in analyses of climate change for other water systems (e.g., the Colorado River Basin).

Lund et al. estimated the effect of socioeconomic and climate changes on statewide allocations of water using the CALVIN model. Figure 44 displays statewide changes in volumetric scarcity. This is the amount of water users desire (and would be willing to pay for), but is not delivered to them. The Base 2020 bar gives scarcity amounts assuming that current legal and institutional constraints continue. The next bar shows how much lower the scarcity costs would be if there were no constraints. The SWM2100 bar shows the effect of population growth alone. Results should be compared to the SWM2020 bar because both assume free market conditions. Interestingly, urban scarcity increases six-fold, while agricultural scarcity doubles. The volumetric scarcity for agriculture is much larger than for urban users.

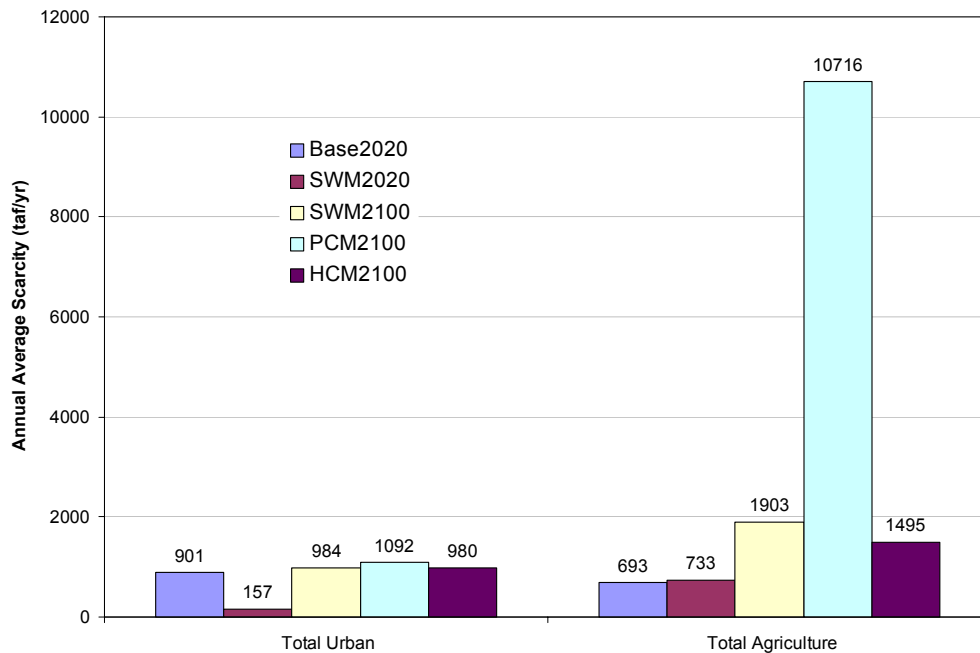


Figure 44. Total Volumetric Scarcity

The last two bars in each set, PCM2100 and HCM2100, display the effect of the climate change scenarios. The effect of climate change on urban users is estimated to be far smaller than the effect on agriculture users. Water scarcity for urban users increases very slightly under the dry PCM scenario and decreases very slightly under the wet HadCM2 scenario. Deliveries to urban users are hardly affected by climate change. In contrast, water scarcity for agriculture increases by almost 9 million acre-feet, or five-fold, under PCM, while it decreases by 400,000 acre-feet under HadCM2. In general, changes in supply tend to be taken out of or added to agriculture rather than urban uses.

Table 12 estimates operating and “scarcity” costs (what water users would be willing to pay for water supplies that they desire but are not delivered to them). The third column shows how much lower the scarcity costs would be if there were no constraints in 2020 compared to the case with continued legal and institutional requirements. Interestingly, operating costs would not be affected. With population growth from 2020 to 2100, scarcity costs for urban uses increase four-fold and for agriculture uses increase almost seven-fold. Meanwhile, operating costs more than double.

Table 12. Summary Of Statewide Operating And Scarcity Costs

Summary Of Statewide Operating And Scarcity Costs (\$Millions)					
Cost	Base 2020	SWM2020	SWM2100	PCM2100	HCM2100
Urban scarcity costs	1,564	170	785	872	782
Agric. scarcity costs	32	29	198	1,774	180
Operating costs	2,581	2,580	5,918	6,065	5,681
Total costs	4,176	2,780	6,902	8,711	6,643

The effects of climate change are comparatively quite small on urban users and much larger on agriculture users. The effects on operating costs are also relatively low. The estimated scarcity cost to agriculture of the PCM scenario is about \$1.5 billion. Note that this analysis does not consider how agriculture could allocate reductions among low and high water using crops. The effect here is higher than what is calculated in the agriculture study (see Section 3.2.5). Figure 44 and Table 12 show that population growth is projected to have a much greater effect on urban water use and operating costs than does climate change. However, the effect of climate change on agriculture water deliveries is greater than the effect of population growth. In general, urban users are less affected by either growth or climate change because they are willing to pay more to obtain supplies and because they use a small portion of water relative to agriculture.

Lund et al. also estimated how water deliveries to different regions of California could be affected by climate change. Figure 45 displays deliveries and scarcities statewide and for major regions. Population growth alone results in southern California having greater total demand than Tulare, although southern California is faced with more scarcity without climate change.

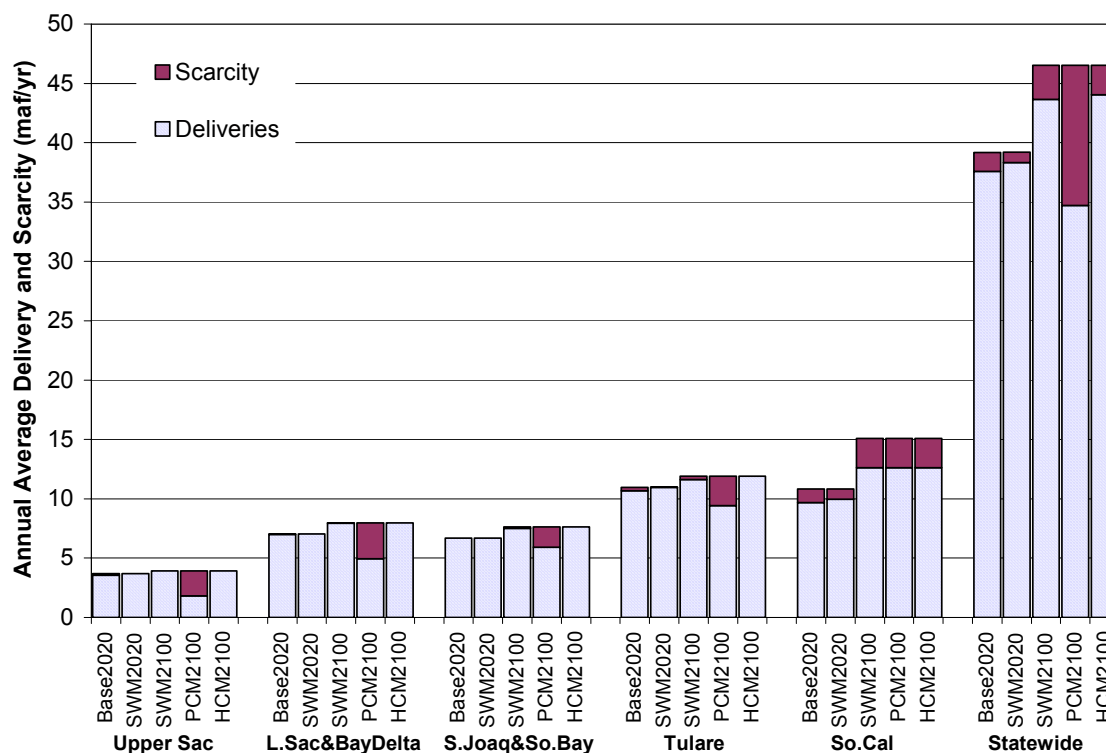


Figure 45. Total Water Deliveries And Scarcities By Region And Statewide

Interestingly, climate change, and in particular the PCM scenario, has little effect on deliveries to southern California, but reduces deliveries to the other regions. This is partly because agriculture water use in southern California is reduced by population growth and because southern California can draw on the Colorado aqueduct (whose supplies are assumed to remain unchanged). Indeed, the most limiting factor for southern California is the size of conveyance systems, which includes the California and Colorado Aqueducts. In contrast, other regions would have reduced supplies under the PCM scenario, but would have all of their needs met under the HadCM2 scenario.

Lund et al. examined the effect of climate change and population growth on environmental constraints. Table 13 displays the marginal (shadow) costs to other users to provide runoff to satisfy environmental constraints (or their willingness to pay, WTP, to satisfy environmental demands). Population growth alone increases WTP in many of the rivers and refuges. However, the effect of the PCM scenario is much greater than the effect of population growth. Lund et al. estimate that even if all water were used to meet instream environmental needs, there would not be enough runoff in the Trinity and Sacramento rivers and in the Mono Lake inflow to meet current environmental needs. In contrast, the wet HadCM2 scenario results in lower WTPs than does no climate change, and even lower than does 2020 population and no climate change in many cases. This implies that runoff under HadCM2 would be greater even under 2020 conditions. Such outcomes as increased loading of sediments and nutrients were not considered in the analysis.

Table 13. Shadow Costs Of Environmental Requirements

Shadow Costs Of Environmental Requirements				
	Average WTP (\$/AF)			
	SWM2020	SWM2100	PCM2100	HCM2100
Minimum instream flows				
Trinity River	0.6	45.4	1,010.9	28.9
Clear Creek	0.4	18.7	692.0	15.1
Sacramento River	0.2	1.2	25.3	0.0
Sacramento River at Keswick	0.1	3.9	665.2	3.2
Feather River	0.1	1.6	35.5	0.5
American River	0.0	4.1	42.3	1.0
Mokelumne River	0.1	20.7	332.0	0.0
Calaveras River	0.0	0.0	0.0	0.0
Yuba River	0.0	0.0	1.6	1.0
Stanislaus River	1.1	6.1	64.1	0.0
Tuolumne River	0.5	5.6	55.4	0.0
Merced River	0.7	16.9	70.0	1.2
Mono Lake inflows	819.0	1,254.5	1,301.0	63.9
Owens Lake dust mitigation	610.4	1,019.1	1,046.1	2.5
Refuges				
Sac West Refuge	0.3	11.1	231.0	0.1
Sac East Refuge	0.1	0.8	4.4	0.5
Volta Refuges	18.6	38.2	310.9	20.6
San Joaquin/Mendota Refuges	14.7	32.6	249.7	10.6
Pixley	24.8	50.6	339.5	12.3
Kern	33.4	57.0	376.9	35.9
Delta outflow				
Delta	0.1	9.7	228.9	0.0
a. SWM2100 results do not include hydropower values (except for Mono and Owens flows).				

Lund et al. calculated the value of increasing storage and conveyance. Not surprisingly, the value of increased storage rises with the dry PCM scenario, but drops with the wet HadCM2 scenario. What is surprising is that the value of expanding conveyance, i.e., the canals and aqueducts that move water around the state, increases under both scenarios.

Finally, hydropower production is estimated to decrease in the PCM scenario and increase in the HadCM2 scenario. Changes in monthly average hydropower energy generation are

displayed in Figure 46. Generation under the PCM scenario would fall in all months. In the wet HadCM2 scenario, generation would increase in winter months but decrease in summer months. In contrast, as is discussed in Section 3.3.1, demand for electricity for heating in the winter would drop, and demand for electricity for cooling would increase; it is reasonable to expect the largest increase in the summer. So, the change in supply and demand would be mismatched. Under the PCM scenario, hydropower revenues would be reduced by 30%; under the HadCM2 scenario, they would increase by more than 50%.

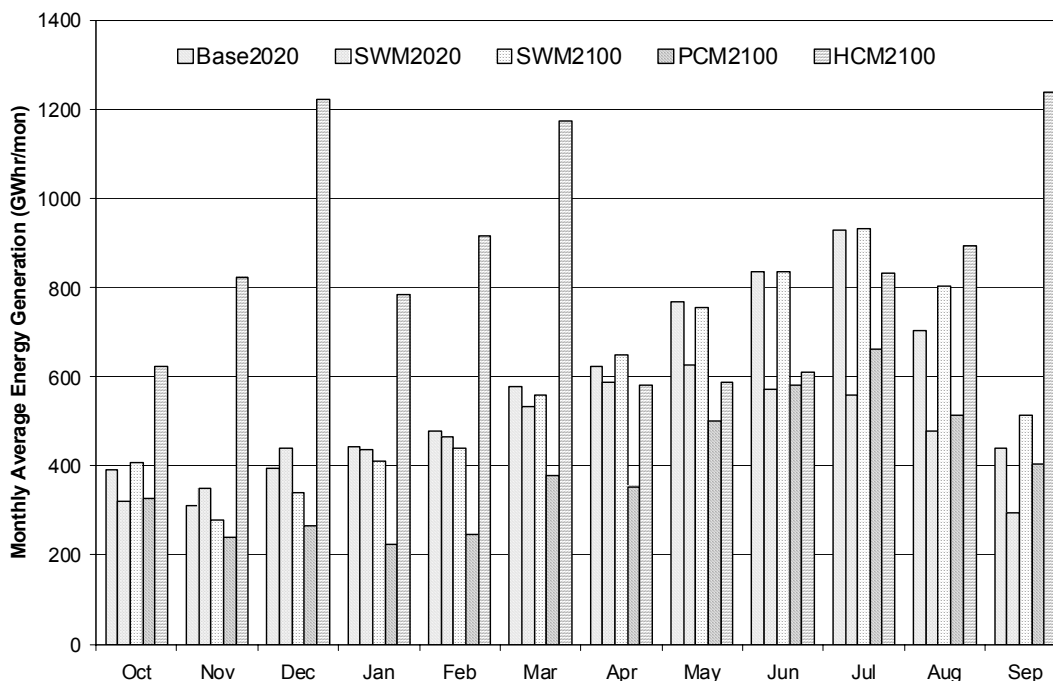


Figure 46. Monthly Hydropower Generation From Major Reservoirs

3.2.4. Crop Yields

California has a wide diversity of crops, which makes it a challenge to estimate how these varied crops will be affected by climate change. Physiological crop models exist for the key grain crops — such as wheat, corn, and soybeans — that dominate much of U.S. agriculture. Such models do not exist, however, for many of the high value crops grown in California. To estimate change in crop yields as a function of climate for this study, Adams and Wu (Appendix IX) used a statistical approach. They regressed county-level crop yields on monthly growing season temperature and precipitation in California to develop statistical relationships between climate and yield. They also estimated potential carbon fertilization effects (higher CO₂ levels increase plant growth in some species) based on the literature, and considered the effect of different soil types. Higher CO₂ levels also result in decreased demand for water, but this study did not take that into account. Finally, crop yields have been steadily increasing throughout the last 50 years, and Adams and Wu examined the effects of future technological improvement in crop yields based on the literature and the judgment of the investigators.

To develop crop yield estimates, the researchers assumed that irrigation water is initially available at base year quantities. Climate change could result in decreased water supplies for irrigation because of decreased surface water deliveries or other higher demands for water, and this was addressed in the water resources and agriculture studies.

Higher temperatures tend to increase yield per acre in the northern and coastal regions, but they tend to decrease yields in the San Joaquin and desert areas (see Figure 47). This is partly because the northern and coastal regions are cool and can benefit from more heat. In addition, crops such as corn and sugar beets prefer hotter temperatures. However, crops such as potatoes have reduced yield because they prefer colder temperatures. The effect of climate change on individual crops varies widely; some show substantial increases in yields, and some could see substantial decreases. Demand for irrigation per acre rises with higher temperature, although this estimate does not account for the effect of increasing water use efficiency at higher CO₂ concentration levels.

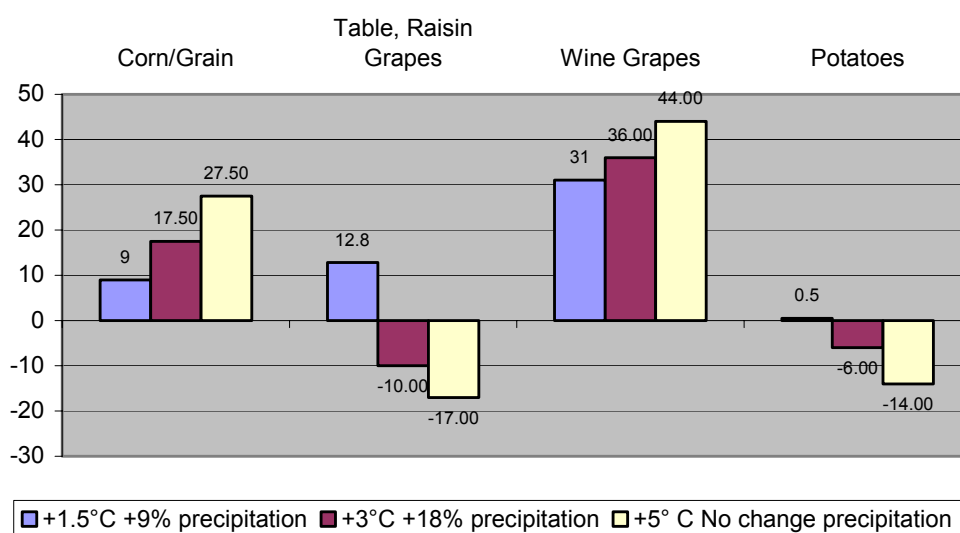


Figure 47. Change In Crop Yields With CO₂ Fertilization In The Sacramento And Delta Regions Of California

Yields are very sensitive to assumptions about technological changes and the CO₂ fertilization effect. Improved technology can substantially increase average yields. However, the study assumed that technology does not change sensitivity to climate; a drought could still substantially reduce yields. CO₂ fertilization can substantially offset decreases in yields from climate change.

Increased precipitation during the growing season is beneficial for many crops, but not for all. For example, grapes grown for wine production are adversely affected by increased summer precipitation.

Note that the discussion to this point has focused on changes in yields per acre. To estimate how aggregate production changes, the yield changes must be integrated with the changes in water supplies, which is addressed in the next section.

3.2.5. Agriculture

The Statewide Water Agricultural Production (SWAP) model is an economic optimization model that identifies demand for water (input) for each region in California, along with the resulting value of agricultural output (Appendix X). By using a supply-demand approach, SWAP is able to compute the “shadow value”⁶ per unit of water, by region and by month. This approach explicitly recognizes the effect of high user prices on water demand, and conversely the effect of the willingness to pay for water reliability. The solution maximizes the value of water across all uses subject to spatial water constraints, which include physical limitations on water availability, storage, and transfer. The model adjusts water production and allocation over the year in such a way that the marginal value of water is equated across irrigation months.

SWAP’s objective is to maximize each region’s total net returns from agricultural production subject to pertinent production and resource constraints on water and land. Production constraints take the form of functional relationships that describe the productive tradeoffs between land and water use efficiency, in conjunction with capital cost expenditures. The model uses water in production based on each region’s initial annual allocation and the production opportunities facing the region. It assumes a perfectly competitive market structure in which producers are not able to influence prices in either input or output markets; each producer is perceived as being relatively small in relation to the market. Furthermore, this model is calibrated against observed data and is consistent with microeconomic theory, which asserts that productive decisions are based on marginal conditions. In contrast, published data are based on average conditions. The SWAP model is “positive” in that it uses the farmers’ actual crop and input allocations in a given region and year to derive the marginal product and land value relationships (Lund and Howitt, 2001).

The SWAP model captures the three ways in which farmers can adjust crop production when faced with changes in the price or availability of water. The total amount of irrigated land in production can change with water availability and price. We see this reaction particularly during California’s periodic droughts, when the largest reduction in water use comes from reducing the number of irrigated acres. The second avenue of adjustment is to change the mix of crops produced to increase the value produced by a unit of water. The third approach measures the changes in the intensity of input use on the crops that are grown.

The monthly functions that estimate the economic value of water for 24 regions of SWAP (see Figure 48) are transferred to the CALVIN model, where they are used to determine the optimal statewide allocation of water supply across 72 years of variable hydrology.

6. Shadow value is the marginal value of having another unit of the resource, that is, the change in the profit from being able to relax a constraint by one unit.

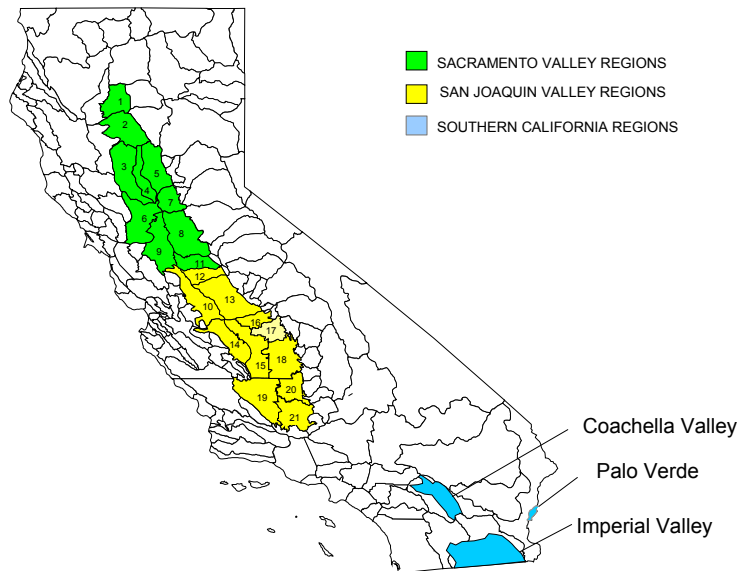


Figure 48. California Map With Southern And Northern SWAP Regions

One key step in this analysis was forecasting changes in the demand for crops. The investigators used two different techniques to forecast demand for California commodities in 2100. For a short-term forecast to 2020, time-series analysis techniques were used with the existing 30 year database. For the long-term horizon spanning 2020 to 2100, income elasticities for the commodities and income and population projections were used as a basis for the forecast (see Appendix II). Another key step was to forecast change in land use: Landis and Reilly's results (Appendix III) were used to project shifts of agricultural land to urban uses.

Changes in demand will lead to a shift in the mix of crops grown. The analysis finds that the percentage of land in high-value crops could increase from 42% in 2020 to 67% in 2100.

Crop yields have been increasing since World War II at 2% per year (Adams et al., 1999). It is not reasonable to assume that crop yields will continue to increase at such a rate. This additional yield increase was set at 0.25% per year after much discussion among the research team members and university agronomists. The smaller than historical technological effect was purposely chosen because the very long forecast horizon magnifies any small discrepancy in annual technological change. Over the horizon, the 0.25% compound technological change resulted in a 28% increase in yield.

The increase in population results in a shift in water away from agriculture, netting a decrease of water use in agriculture of about 10%. Agricultural land use is projected to decrease by a smaller percentage. In spite of this, agricultural income is projected to more than triple mainly because of increases in demand for high value crops.

Figure 49 displays the changes in crop yields for the north region of the Central Valley under the +3°C, +18% precipitation scenario with and without technological improvement. Both effects increase yields, although the technological change has a much greater effect than climate change.

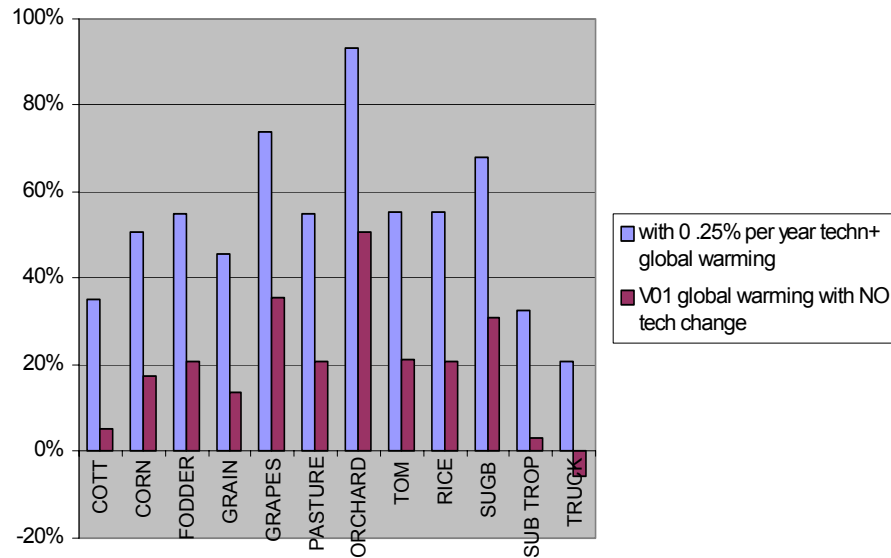


Figure 49. The Basis Of Yield Changes Under 3°C, 18% P Scenario, With And Without Annual Technological Change (0.25% Per Year) – North Region Of Central Valley (2000-2100)

Irrigation requirements will also change. Higher temperatures will most likely increase demand for irrigation, although this can be offset to some extent by increased precipitation or the CO₂ fertilization effect. Figure 50 shows the changes in irrigation requirements for the +3°C, +18% precipitation scenario. The study found that demand for irrigation would decrease in the 2020s, but increase by the end of the century.

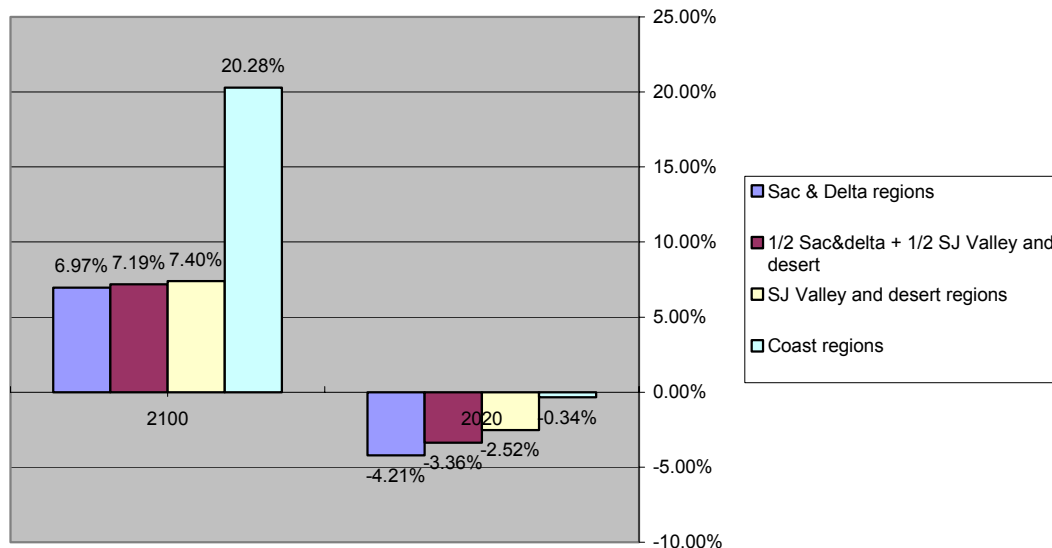


Figure 50. Regional Percentage Changes In Water Requirement In 2020 And 2100, Under The +3°C, +18% P Scenario

In contrast, the HadCM2 scenario, which has increases in summer temperatures in the agricultural regions of 3°C to 4°C, but is substantially wetter in winter than the incremental scenario and somewhat wetter in summer, shows a higher increase in demand for irrigation (see Figure 51).

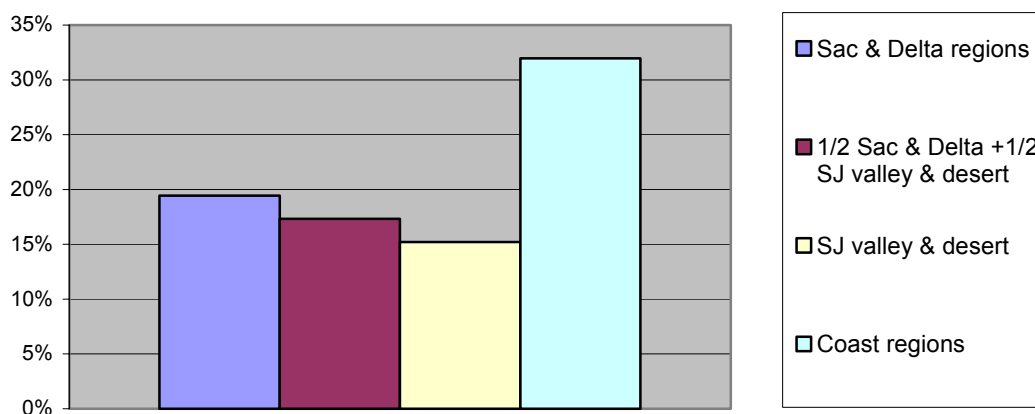


Figure 51. Regional Percentage Changes In Water Requirement In 2100, Under The Hadcm2 Scenario

One of the more interesting questions is how agricultural production would be affected by changes in water supply. Agriculture consumes the most water and, on average, has a lower value of use compared to other water consumers. Consequently, agriculture usually bears the brunt of any decrease in supply. The HadCM2 scenario results in an increase in the state's water supply and an increase in water deliveries to agriculture. This results in only a negligible increase in output or income.

The PCM scenario presents an interesting contrast between change in supply and economic impact. The average results for California are displayed in Figure 52. The SWAP model allocates reductions in inputs and change in production based purely on economic efficiency, i.e., where application of water will yield the greatest economic return. Water supply is reduced by 24%. However, changes in crops and adoption of more efficient irrigation practices reduces irrigated land area by 15%. Since SWAP estimates that the decreases in crop production are concentrated in the lower valued crops, the reduction in the gross value of production of approximately \$1 billion is yet a smaller proportion at 8%. The final reduction of 6% in net income is the result in part of increases in crop prices slightly offsetting the reduction in acres. The percentage reduction in agricultural income is much lower than the percentage change in water supply, displaying the potential of the agriculture sector to reduce the potential adverse effects of climate change through adaptation. (Note also that the estimated loss of \$1 billion is less than the estimated loss to agriculture from the water study of \$1.5 billion. This could be considered the potential effect of adaptation in the agriculture sector.) The average reduction in expenditures by irrigated agriculture is 16%.

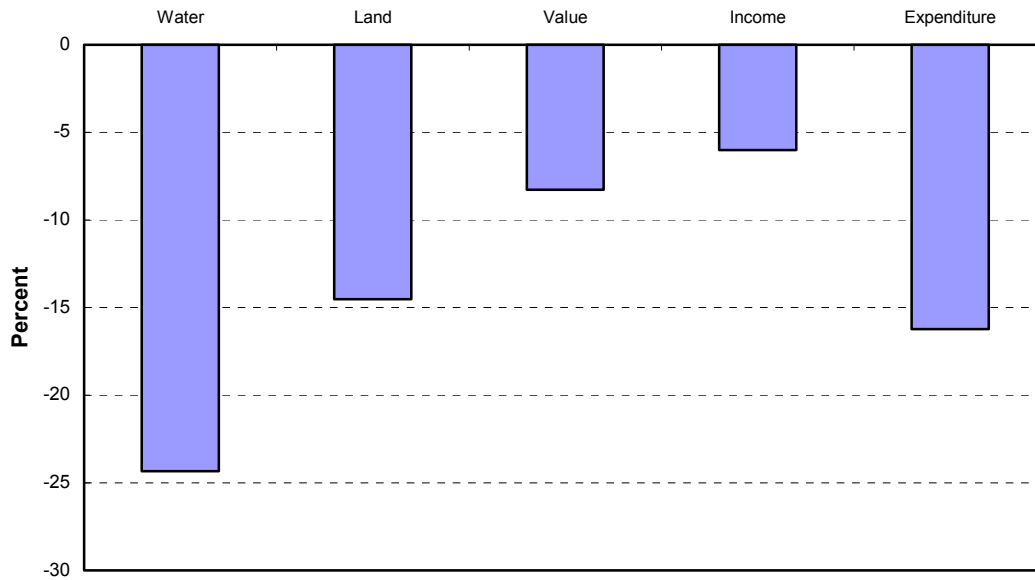


Figure 52. Average PCM Effect On Water Consumption, Land Use, Land Value, Income, And Expenditures

The rather small changes in statewide income mask wide regional disparities. Figure 40 displays changes in water use, land use, and income for 21 regions within the Sacramento and San Joaquin valleys. These regional changes differ not only in magnitude, but also in sign. Although statewide deliveries of water to agriculture are reduced by one-quarter, regions 6 (in the Sacramento Valley), 10, and 21 (in the San Joaquin Valley) get slight increases in water deliveries. Land use and income in those regions also rise. In contrast, regions 3, 5, and 7, all in the Sacramento Valley, face reductions in water deliveries of more than 70 to 80%. Agricultural land use in those regions declines by more than 60%, while income is reduced by approximately one-third to one-half. Furthermore, Palo Verde, along the Arizona state line, is assumed to virtually cease agricultural production. It is interesting that decreases in production are in both southern areas (Palo Verde) and northern areas (Sacramento Valley). There does not appear to be a relationship between latitude and change in output, as has been exhibited in studies of impacts of climate change on national or global rainfed agriculture (Rosenzweig and Parry, 1994; Adams et al., 1999).

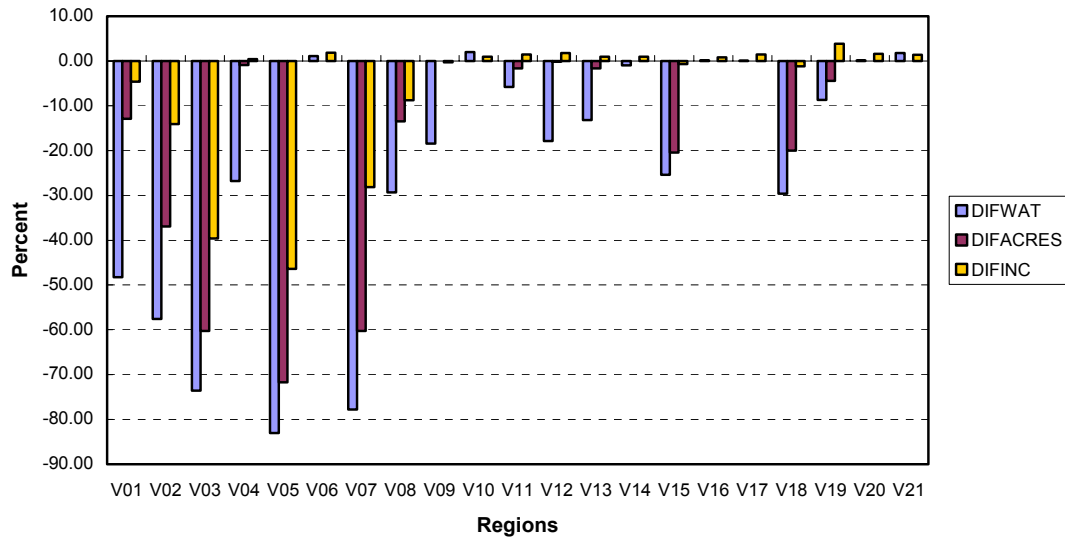


Figure 53. PCM Differences In Water Availability, Acreage, And Income From SWM By Region (See Figure 48)

3.3. Other Impacts

Many other important sectors will be affected by climate change. This project also addressed climate change impacts on energy demand (effects on the supply of electricity from hydropower were modeled as part of the water resources study), coastal market resources, and human health. We discuss the results of these studies in the sections that follow.

3.3.1. Energy

Energy expenditures are sensitive to climate. In particular, the demand for interior space heating and cooling is strongly affected by climate and will be affected by climate change.

In this study (Appendix XI), Mendelsohn estimated the response to climate change of energy use for space heating and cooling in residences and businesses across California. The study also considered the implications of changes in income over time, which can result in different investments in capital, such as the installation of more air-conditioning systems. It assumed that average energy prices increase 1% per year in real terms in the 21st century. The study used cross-sectional analysis to relate climate to energy demand, similar to the approach used in the crop yield studies. To obtain sufficient variation in climate, Mendelsohn used data on energy demand from the lower 48 states. The study examined both short-run and long-run models. The short-run models freeze building characteristics. The long-run model allows some building characteristics such as insulation and cooling capacity to adjust as climate changes.

Before examining how climate change could affect energy expenditures, we must first understand the relationship between current climates and observed energy expenditures. In the residential and commercial sectors, warmer January temperatures reduce expenditures because less space heating is needed. In the residential sector, warmer July temperatures reduce energy use — if average temperatures remain below 20°C (68°F) — because of less demand for space heating. Above that threshold, however, energy use increases because of more demand for cooling. In the commercial sector, the threshold above which July energy demand increases (because of increased cooling needs) is 15.8°C (60°F). The inflection point for commercial energy

demand is lower than the inflection point for residential demand because commercial buildings generate substantial heat from lighting and equipment, they are larger (requiring more cooling), and, in many retail establishments, temperatures are kept cool to attract customers.

Higher temperatures from climate change are estimated to result in higher annual energy expenditures for the residential sector (Figure 54). These increases are estimated to range from \$1.6 billion to \$10.2 billion by 2100. The increased use of energy for cooling is much larger than the reduced use of energy for heating. Warming thus increases energy costs on net. The long term energy expenditures are even higher than the short term expenditures because consumers are predicted to increase cooling capacity as a long term adaptation to climate change.

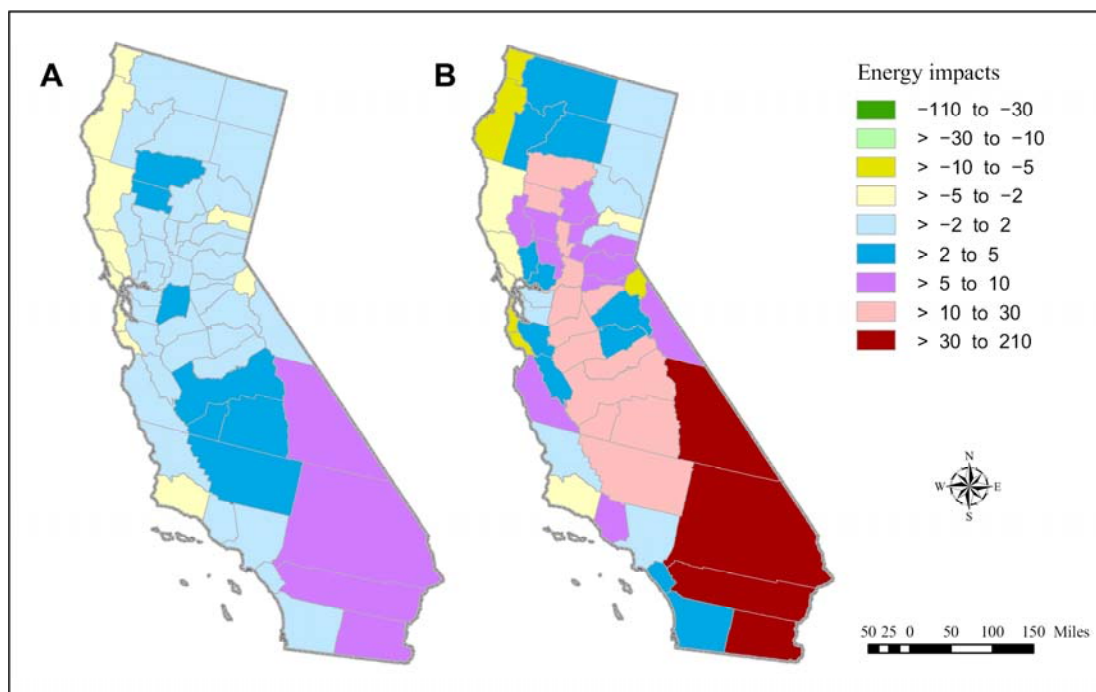


Figure 54. Residential Energy Impact (Percentage Change In Energy Expenditures) By County Based On The Climate Scenarios: A) 1.5°C And 9% Precipitation, B) 5.0°C And 0% Precipitation

The commercial sector also faces increased annual energy expenditures (Figure 55). The energy expenditures for this sector increase by about \$300 million to \$8.7 billion, depending on the amount of increase in temperature (higher temperatures result in greater expenditures) and on whether buildings are assumed to be unchanged or adjustments are made in response to climate change. The main adjustment would be installation of air conditioning, which results in even larger increases in energy expenditures.

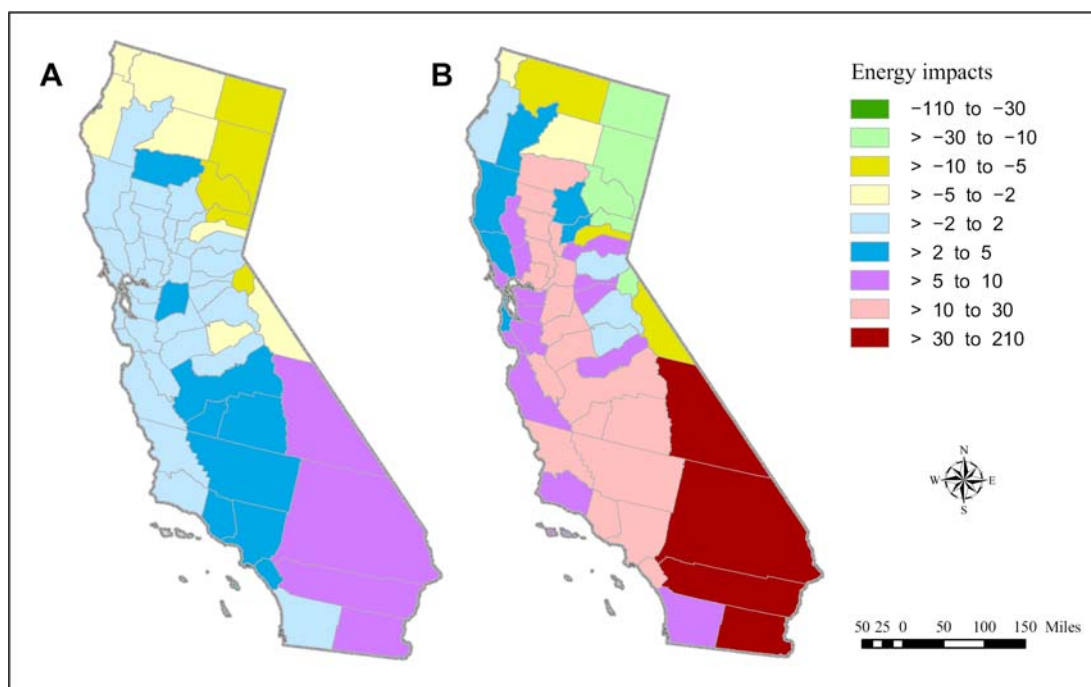


Figure 55. Commercial Energy Impact (Percentage Change In Energy Expenditures) By County Based On The Climate Scenarios: A) 1.5°C And 0% Precipitation, B) 5.0°C And 0% Precipitation

Total energy expenditures are also estimated to rise, with greater increases estimated with higher temperatures. By 2020, the GCM climate change scenarios could result in an increase of energy expenditures ranging from 0.5% to 6%. By 2060, the increase is 6% to 9%. Table 14 displays changes in total energy expenditures by 2100, accounting for the possibility of faster or slower technological change and increased penetration of air conditioners (“slow” vs. “fast”). In addition, the analysis assumes that buildings do not change in response to climate change (“short-run”) or change (“long-run”). Total energy expenditures for the state in 2100 are estimated to rise \$1.9 billion to \$3.5 billion (4% increase) for a 1.5°C warming and from \$9.4 billion to \$18.9 billion (15 to 21% increase) for a 5°C warming. Increased expenditures are 10% to 24% higher when long-term modifications such as additional installations of air-conditioning are taken into account.

Table 14. Increase In Annual California Commercial, Residential, And Total Energy Expenditures By 2100

Increase In Annual California Commercial, Residential, And Total Energy Expenditures By 2100 (\$ million)						
Scenario	Residential		Commercial		Total	
	Short-run	Long-run	Short-run	Long-run	Short-run	Long-run
1.5°C, 0% P						
Slow	1,609	1,596	333	503	1,942	2,099
Fast	2,154	2,293	599	906	2,753	3,199
1.5°C, 9% P						
Slow	1,764	1,794	333	503	2,097	2,297
Fast	2,411	2,622	599	906	3,010	3,528
3.0°C, 0% P						
Slow	3,158	3,820	1,370	1,791	4,528	5,611
Fast	4,306	4,854	2,468	3,226	6,774	8,080
3.0°C, 18% P						
Slow	3,462	3,712	1,370	1,791	4,832	5,503
Fast	4,807	5,501	2,468	3,226	7,275	8,727
5.0°C, 0% P						
Slow	5,440	6,054	3,939	4,850	9,379	10,904
Fast	7,735	9,125	7,095	8,736	14,830	17,861
5.0°C, 30% P						
Slow	5,934	6,700	3,939	4,850	9,873	11,550
Fast	8,545	10,187	7,095	8,736	15,640	18,923
HadCM2 2100						
Slow	4,219	4,740	1,973	2,522	6,192	7,262
Fast	5,915	7,099	3,553	4,543	9,468	11,642
PCM 2100						
Slow	3,067	2,947	1,172	1,534	4,239	4,481
Fast	4,010	4,126	2,111	2,763	6,121	6,889

There are important regional differences in how energy expenditures could be affected by climate change. These depend heavily on whether regions are already warm and using more energy for cooling, or currently cool and using more energy for heating. Not surprisingly, energy demand increases most in the southeastern desert areas, and northern maritime and high alpine counties show the smallest changes in energy expenditures. The southern Central Valley experiences increases in energy demand comparable to the desert, and northern Central Valley and southern maritime counties experience intermediate impacts.

3.3.2. Coastal Market Resources

Much of California's coastline is dominated by cliffs and is rising in some areas. As a result, the coastline's vulnerability to climate change is relatively low compared to that of the coasts of the southeastern United States. However, many parts of the coast are low-lying, highly populated, and exposed to sea level rise. If no countermeasures were taken, the greatest impacts of sea level rise would be in the coastal region between San Diego and Santa Barbara, and in San Francisco Bay. These areas would be affected because of their lower lying topography and the density and coastal proximity of high-value property.

In this study, Newmann estimated the cost of protecting low-lying coastal areas plus the value of land that is not protected and eventually inundated (Appendix XIII). The analysis focused mainly on developed coastal areas and did not include coastal wetlands. The scenarios of sea level rise by 2100 are 33 cm, 50 cm, 67 cm, and 100 cm, capturing a wide range of potential changes in sea level rise (Houghton et al., 2001). The study used the Yohe et al. (1999) model to estimate economic impacts of sea level rise at each site assessed. The Yohe model assumes that decisions on protection versus abandonment of coastal property are based on benefit-cost analysis, with a single decision maker maximizing societal welfare. Past experience reveals that the influence of wealthy and politically powerful coastal property owners combined with government funding for coastal protection can result in more coastal defense measures than the model might project as economically justified. However, in most of the sensitive coastlines in California, the model predicts that it is efficient to protect all market property from inundation, so this observed behavioral bias was not important in this analysis.

This study builds on previous national studies of sea level rise impacts (Titus et al., 1991; Yohe et al., 1999), which examined only three sites in California, none of which were south of Santa Barbara. A limited number of sites may have been sufficient for a national study, but are insufficient for a study focusing on California. This study added sites to allow sufficient diversity of characteristics for extrapolation to the full California coast. The four new sites chosen were Imperial Beach; Ano Nuevo, a cliff site south of San Francisco; Palo Alto, which includes several low-lying residential areas; and Ferndale, along Humboldt Bay (Figure 43).



Figure 56. Sea Level Rise Study Sites

Even when the four sites are added, one of the key limitations of the analysis remains — the lack of a site in the low-lying Los Angeles area. To overcome this limitation, Neumann and colleagues conducted a sensitivity analysis assuming that the entire area between Los Angeles and San Clemente will be protected by beach nourishment and armoring. This is an overestimate, because some parts of the coast in that area will not need protection because of topography or degree of development.

The estimates of protection costs and value of inundated land did not include the costs of protecting low-lying and valuable land in the San Joaquin Delta. In addition, this study did not estimate the economic value from lost services from inundated wetlands. Sea level rise and coastal defense measures such as those assumed in this study can result in a significant loss of wetlands.

An additional limitation of the study is that it examined only sea level rise, not changes in coastal storms. Sea level rise and higher sea surface temperatures can make coastal storms more destructive.⁷ Should the intensity or frequency of coastal storms increase, damages from climate change to coastal resources would increase as well.

The undiscounted cost of the effects of sea level rise on coastal resources of California over the next 100 years is approximately \$700 million for a 50 cm sea level rise and \$4.7 billion for a 1 m sea level rise. These figures assume complete protection of the area between Santa Monica and San Clemente, an assumption that most likely overstates costs. If we do not assume complete protection, the undiscounted costs are \$400 million for a 50 cm sea level rise and \$2.2 billion for a 1 m sea level rise. The discounted value is estimated to be between \$46 million and \$123 million for a 50 cm sea level rise and \$198 million and \$635 million for a 1 m sea level rise

7. Higher sea level can result in further landward inundation of storm surges, and higher temperatures can result in greater intensity of tropical storms.

(Figure 57) assuming complete protection of southern California. The figures are one-quarter to one-third lower if complete protection for southern California is not assumed. The results vary depending on the rate of sea level rise, the process used to scale results from the site level to the entire state, and whether a discount rate of 0%, 3%, or 5% is used. The discounted costs are much smaller than the undiscounted costs because most of the protection costs are in the latter half of this century, when even a low discount rate can significantly reduce present values (see Figure 58 and Figure 59). Annual costs for a 50 cm sea level rise by 2100 were estimated to range from \$8 million to \$15 million. Annual costs for a 1 m sea level rise were estimated to range from \$40 million to \$100 million.

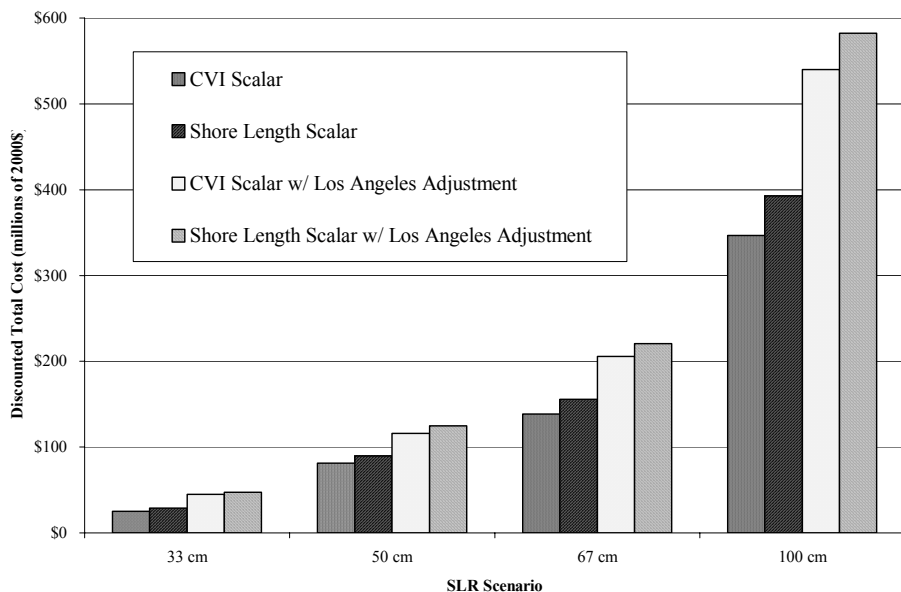


Figure 57. California's Discounted Economic Cost Of Sea Level Rise

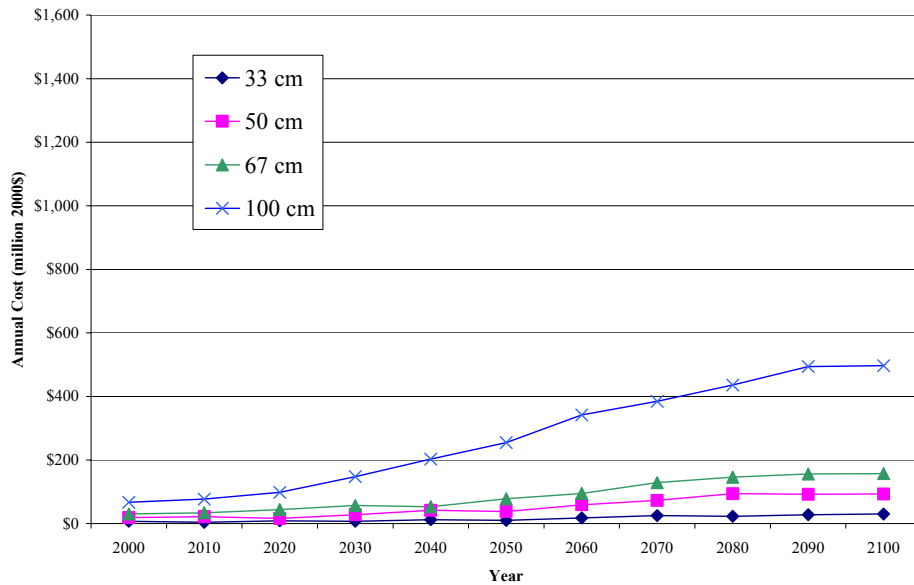


Figure 58. California Transient Undiscounted Costs Of Sea Level Rise By Decade Without Los Angeles Adjustment

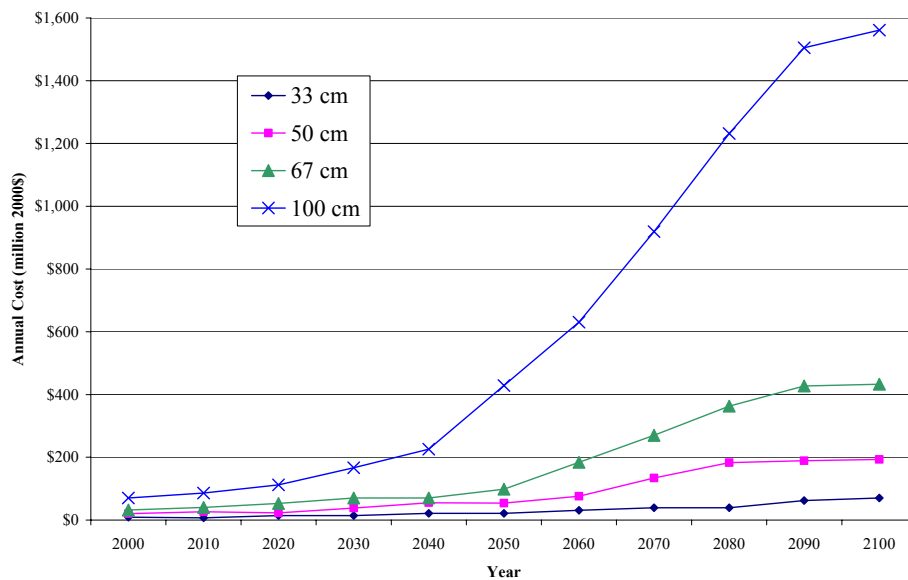


Figure 59. California Transient Undiscounted Costs Of Sea Level Rise By Decade With Los Angeles Adjustment

The study suggests a possible role for coastal planning, particularly to protect wetlands by enabling them to migrate inland in response to sea level rise without being blocked by coastal development. Farsighted land use planning around wetland areas may ensure that dry land just landward of vulnerable wetlands is protected from development, allowing wetlands to retreat and enabling at least a portion of the ecological value of wetlands to be maintained.

3.3.3. Human Health

This study (Appendix XIV) examined the sensitivity of health to weather and climate variability using recent data from California. Note that unlike the other studies in this project, the health study did not address how future climate change may affect human health. The results add a new perspective to the current body of research, much of which has relied on scenarios of potential future effects rather than on empirically estimated effects.

Previous research on the relationships between climate and human health demonstrated that climate variability could affect the incidence and distribution of weather-sensitive diseases (e.g., Patz et al., 2000). Weather and climate variability are known to be directly associated with health effects such as heat stroke and illness, injuries, and deaths that occur during or following extreme weather events. Other adverse health effects — such as morbidity and mortality related to air pollution and illnesses associated with water-, food-, and vector-borne microorganisms — are indirectly related to weather and climate. In addition, many infectious diseases are affected by weather patterns and climate variability, although the relationships are not well understood. A better understanding of these relationships is essential to identify potential health concerns associated with climate change and to devise public health responses to minimize these effects.

In this study, Ebi and Kelsh used time-series regression techniques to examine the relationship between weather patterns — i.e., changes in temperature and the onset of El Niño events — and hospital admissions for viral pneumonia, cardiovascular diseases (angina pectoris, acute myocardial infarction, and congestive heart failure), and stroke. Separate models were estimated for each disease in each of three California metro areas: Los Angeles (defined as Los Angeles and Orange counties), San Francisco (San Francisco and San Mateo counties), and Sacramento (Sacramento and Yolo counties). Data on hospitalizations from 1983 to 1998 were collected, and associations between weather and health were analyzed separately by patient age and gender.

The study found that the weather-health associations varied by geographic region. For viral pneumonia, hospitalizations in the San Francisco and Los Angeles areas increased significantly (30%-50%) with a decrease in minimum temperature. Sacramento area hospitalizations increased significantly (25%-40%) with a decrease in maximum temperature. In the Sacramento area, El Niño events were associated with viral pneumonia hospitalizations, showing significant decreases for girls and increases for women. These weather-health associations were independent of season.

For cardiovascular diseases and stroke, weather variables had the strongest effect on hospitalizations in San Francisco. Decreases in maximum temperatures and increases in minimum temperatures were associated with significant increases in hospitalizations for all types of cardiovascular disease for men and women 70 years of age and older. These increases were most pronounced in men with angina and women with acute myocardial infarction. Men and women aged 55 to 69 years had increased hospitalizations for congestive heart failure. The hospitalization patterns in Sacramento were generally similar to those in San Francisco, but with weaker associations. Decreasing maximum and increasing minimum temperatures affected hospitalizations in a number of age-disease categories. In general, the health effects of temperature variables were weakest in the Los Angeles area, where the team observed fewer weather-health associations.

El Niño events were significantly associated with cardiovascular disease hospitalizations for both men and women in the San Francisco area. In Sacramento, El Niño events increased hospitalizations for acute myocardial infarction and angina, notably in women. In Los Angeles, El Niño events had little health impact.

A single temperature variable failed to explain all the associations observed between weather and hospital admissions in the three California locales. Instead, study findings underscore the complexities of the association between climate and health effects. For example, the associations between viral pneumonia, cardiovascular disease, and stroke hospitalizations and specific weather factors varied across the geographic regions. Consequently, a model based on either the inland region or on one of the coastal regions would not be predictive of the other regions in California.

The strongest association between temperature change and hospitalizations was seen in San Francisco. Residents of that city may be less likely to use heating or air conditioning or other adaptive measures in response to sudden changes in temperature that they view as short-term departures from the seasonal norm. This possibility is consistent with the suggestion that diminishing seasonal patterns of cardiovascular disease may result from the expansion of adequate heating systems and the increased use of air conditioning. These results suggest that it may be possible to reduce the impact of climate variability on health by using adaptive measures (e.g., greater use of air conditioning or heating in unseasonably hot or cold periods).

4.0 Conclusions and Recommendations

This project contains a broader range of climate and socioeconomic scenarios, including transient scenarios, addresses more sectors, examines many sectors at a greater level of detail, contains more integration across related sectors, and addresses potential adaptation in more detail than previous studies of climate change impacts on California. We can draw many key conclusions from this work:

- Increased greenhouse gases will most likely raise temperatures in California at least several degrees (C) in this century. Although changes in precipitation are uncertain, the majority of climate model simulations project increased precipitation during the wet season. However, some models project that wet season precipitation could decrease. Whether annual precipitation increases or decreases is uncertain.
- Socioeconomic changes in California, with or without climate change, are likely to be substantial. For example, the state's population is likely to at least double and could triple over this century. Income is likely to rise much more. These changes will have a substantial effect on the use of California's natural resources, and can increase vulnerability through higher population and property values (more people and property exposed to climate risks) and decrease vulnerability through improved technology and higher incomes (more resources to adapt to climate change).
- Vegetation is estimated to migrate to higher elevations, which will reduce the area covered by alpine and subalpine forests. Higher temperatures and wetter conditions would result in expansion of conifer and mixed evergreen forests, along with grasslands, at the expense of shrublands, arid land vegetation, mixed evergreen woodland, and alpine/subalpine forests. Forests tended to shift and expand in northern California, and grasslands expanded in southern California. In contrast, drier scenarios resulted grassland advancing into the simulated historical range of mixed evergreen woodland and shrubland, even in central and northern regions of the state.
 - Both wetter and drier scenarios resulted in increases in carbon storage in California vegetation of between 3% and 6%. The wetter scenarios resulted in increases of total ecosystem carbon (e.g., 5% under the HadCM2 scenario), but much larger increases in carbon stored in vegetation (e.g., 20% under HadCM2). The dry scenarios also result in increases in total carbon storage, but most of the increase is in soils and litter.
 - Climate change will also affect the frequency and size of fires, with most of the scenarios resulting in increased fires. However, the change in fires is not significant until the latter part of the century. The drier scenarios result in more frequent fires and more area consumed by fires. The wetter scenarios result in larger fires than under the dry scenarios, because under the wet scenario, fuel builds up and burns during the occasional dry years.
- Statewide, climate change has a much more dramatic impact on the statewide diversity of terrestrial vegetation communities (and consequently on biodiversity) than does urbanization, which reduces diversity only slightly. Climate change can have much more substantial, although not necessarily consistent, impacts. Warm and wet scenarios result in little change or even an increase in diversity; warm and dry scenarios reduce community diversity.

- The relative effects of urbanization and climate change may be different on the local scale, particular for habitats already strongly affected by urbanization. Coastal sage scrub (CSS), a valuable ecosystem along California's coastal areas that has already been reduced by 90% by development, could be further reduced by as much as 20% in this century. Only a small fraction of CSS would persist under all the climate change scenarios. More than half of these coastal areas would be threatened by development, which could be areas for conservation.
- Net (undiscounted) revenues for timber harvesting are estimated to increase slightly during the early part of the century and decrease toward the end of the century. If revenues are discounted, producers will realize net gains. If timber prices fall as a result of increased global production, California timber producers will lose revenue in all cases. However, falling prices would provide large benefits to California consumers and would result in net benefits for the state.
- Higher temperatures are likely to have a substantial effect on snowpack, snowmelt, and runoff. Snowpacks will begin to melt earlier in the year, resulting in earlier and higher peak flows. This could result in increased flooding, even under drier scenarios. Changes in total annual runoff tend to depend on changes in precipitation, although there is a small effect of evapotranspiration.
- Water resources are likely to be significantly affected by population growth and climate change.
 - Growth in population to over 90 million results in a one-tenth decrease in water deliveries to agriculture uses and a two-thirds increase in deliveries to urban uses.
 - The PCM scenario results in up to a 26% reduction in runoff from the mountains; the HadCM2 scenario results in increases up to 77%. The incremental scenarios fall between these outcomes, ranging from virtually no change to increases of as much as 28%.
 - Accounting for changes in runoff, groundwater supplies, and evaporation from reservoirs, total water supply is estimated to change from a 12% increase under the HadCM2 scenario to a 25% decrease under the PCM scenario. The results from the incremental scenarios are between these ranges.
- The effects of changes in water supply differ quite substantially across sectors and regions.
 - Water deliveries to urban users change very little under any of the scenarios. This is particularly true for urban users in southern California.
 - Water deliveries to agriculture are more sensitive. Deliveries increase slightly under the wet scenarios and decrease as much as 25% under the PCM scenario.
 - Under the PCM scenario, there would not be enough runoff in the Trinity and Sacramento rivers and in the Mono Lake inflow to meet current environmental needs. In contrast, the wet HadCM2 scenario provides enough instream flow to offset the adverse environmental effects of population growth.

- Hydropower production would increase under the wet scenarios and decrease under the dry. Interestingly, even under the wet HadCM2 scenario, production would decrease in summer months. This is when demand for power could rise as a result of climate change, yielding a mismatch in the change in supply and demand (see below).
- Higher temperatures result in increased crop yields in northern and coastal regions, but decrease yields in the San Joaquin and desert areas. The responses of individual crops vary significantly, depending in part on their tolerance and preference for warm or cool temperatures and wet or dry conditions during the growing season.
 - Improved technology could dramatically increase yields, as it has over the past century.
 - Depending on the type of crop, CO₂ fertilization can increase yields or reduce loss in yields brought on by climate change.
 - Climate change is estimated to increase demand for irrigation water by a few percentage points.
- The SWAP model assumes that low value water users will lose water if there is a shortage. By limiting water losses to low valued users, the reduction in agricultural income is kept modest. Income does not change under the very wet scenario and declines about 6% under the very dry scenario despite a 24% reduction in total water deliveries to agriculture.
- Regional impacts vary much more widely. Some regions in the Sacramento Valley and in southeastern California (Palo Verde) are estimated to have substantial reductions in water supplies for agriculture and, hence, substantial declines in income. The Sacramento Valley is estimated to fare less well than the San Joaquin Valley. In the studies, water is assumed to go to where the marginal product of agriculture is greatest, i.e., where it can result in the greatest income. Lower value agricultural production tends to be denied water most readily so it can get delivered to higher value agriculture.
- Higher temperatures are estimated to increase energy demand and expenditures in California.
 - Increased use of energy for cooling more than offsets reduced use of energy for heating. For the residential sector, these increased expenditures range from \$1.6 billion to \$10 billion by 2100.
 - Annual energy expenditures for the commercial sector increase by about \$300 million to almost \$9 billion, depending on the amount of increase in temperature (higher temperatures result in greater expenditures), and on whether buildings are assumed to be unchanged or modified in response to climate change.
 - Total energy expenditures for the state rise \$1.9 billion to \$3.5 billion for a 1.5°C warming and \$9.4 billion to \$18.9 billion for a 5°C warming. Increased expenditures are 10% to 24% higher when long-term modifications such as more installations of air conditioning are taken into account.

- Not surprisingly, energy demand increases most in the southeastern desert areas. Northern maritime and high alpine counties have the smallest changes in energy expenditures.
- Most developed low-lying coastal areas in California (mainly San Francisco Bay and the coast south of Santa Barbara) would most likely be protected from sea level rise. The undiscounted costs of protection would be \$700 million to \$4.7 billion; the discounted value is \$150 to \$500 million. Most of these impacts will occur toward the end of the century. Statewide annual coastal protection costs by the end of the century range from less than \$10 million to over \$100 million. These figures do not include the costs of protecting islands in the Sacramento-San Joaquin Delta.
- The analysis of climate variability and hospital admissions in Los Angeles, San Francisco, and Sacramento for pneumonia or cardiovascular conditions and strokes found that results varied considerably depending on geography. Hospitalizations for viral pneumonia in the San Francisco and Los Angeles areas increased significantly with a decrease in minimum temperature. Sacramento area hospitalizations increased significantly with a decrease in maximum temperature and increase in minimum temperature. For cardiovascular diseases and stroke, changes in both maximum and minimum temperatures were associated with significant increases in hospitalizations in San Francisco for all types of cardiovascular disease for men and women 70 years of age and older. The strongest association between temperature change and hospitalizations was seen in San Francisco, which may be because fewer residences in San Francisco are consistently temperature controlled.

Partial economic impacts are displayed for 2020, 2060, and 2100 in Table 15, Table 16, and Table 17. Impacts for water and agriculture were estimated only for 2100. Because only a few sectors are reported here, the results should be interpreted with caution. These studies indicate net damages to California's economy, with impacts ranging from hundreds of millions to billions of dollars in the early part of this century and billions to tens of billions of dollars in the latter part of this century. Inclusion of other sectors, such as agriculture, could substantially alter these results.

Table 15. Summary Data: Annual Benefits — 2020

Summary Data: Annual Benefits — 2020 (\$Millions)								
Scenario/ Study	HadCM2	PCM	+1.5° C 0% P	+1.5°C +9% P	+3°C 0% P	+3°C +18% P	+5°C 0% P	+5°C +30% P
Timber	20 to -61	31 to -51			26 to -56	28 to -54	27 to -55	32 to -51
Energy	-1,676 to -2,023	-236 to -374						
Coastal (Sea Level Rise Scenario)				-0.2 to -0.6 (0.33 m)	0 to -0.4 (0.5 m)	-1.7 to -2.5 (0.67 m)	-3.5 to -4.9 (1 m)	
Note: Positive numbers are benefits.								

Table 16. Summary Data: Annual Benefits — 2060

Summary Data: Annual Benefits — 2060 (\$Millions)								
Scenario/ Study	HadCM2	PCM	+1.5° C 0% P	+1.5°C +9% P	+3°C 0% P	+3°C +18% P	+5°C 0% P	+5°C +30% P
Timber	40 to -143	131 to -72			-51 to -213	-51 to -214	-45 to -209	-21 to -290
Energy (Assuming Price Increase)	-4,013 to -5,218	-2,687 to -3,700						
Coastal (Sea Level Rise Scenario)				-1.2 to -2.6 (0.33 m)	-4.7 to -6.6 (0.5 m)	-6.9 to -13.2 (0.67 m)	-29.2 to -47.4 (1 m)	
Note: Positive numbers are benefits.								

Table 17. Summary Data: Annual Benefits — 2100

Summary Data: Annual Benefits — 2100 (\$Millions)								
Scenario/ Study	HadCM2	PCM	+1.5°C 0% P	+1.5°C +9% P	+3°C 0% P	+3°C +18% P	+5°C 0% P	+5°C +30% P
Urban Water Use	3	-87						
Operating Costs Water System	237	-147						
Agriculture	15	-1,113						
Timber	76 to -140	86 to -132			-124 to -390	-93 to -266	-159 to -315	-86 to -261
Energy (Assuming Price Increase)	-6,192 to -11,642	-4,239 to -6,889	-1,942 to -3,119	-2,097 to -3,528	-4,528 to -8,080	-4,832 to -8,727	-9,379 to -17,861	-9,873 to -18,923
Coastal (Sea Level Rise Scenario)				-2.2 to -5.7 (0.33 m)	-7.9 to -15.2 (0.5 m)	-12.4 to -30.3 (0.67 m)	-39.3 to -104.0 (1 m)	
Note: Positive numbers are benefits.								

On the whole, there is potential for climate change to have significant economic impacts in some sectors and more limited impacts in other sectors. The costs may be greatest in the energy sector, measured in billions, and quite possibly more than \$10 billion per year. Other sectors may have economic losses, but at a smaller scale than might be expected given changes in conditions they could face. In the most severe scenario we analyzed, agriculture would have 25% of its water supplies reduced (from an already reduced base supply as a result of population growth) and still only have a \$1 billion loss (8%). Coastal impacts are estimated to be tens of millions to as much as \$100 million per year by 2100. These economic impacts seem like a lot of money and yet also appear relatively small compared to California's economy. The economy is currently over \$1 trillion per year and is likely to be much larger when the climate change impacts are fully realized.

Many impacts were not quantified in economic terms. Increased floods or flood protection were not estimated. Nor were the costs of increased fire or fire protection.

It is important to keep in mind that the impacts of climate change are not spread evenly across California. Some regions could experience much greater relative impacts than the state as a whole. This is particularly true in agriculture, where some regions face reductions in agricultural income of up to one-half. In rural communities, such impacts could be quite significant. For example, Palo Verde in the south and some parts of Sacramento Valley in the north were shown to be at risk for substantial reductions in deliveries of water for irrigation and, hence, reductions in agricultural production. Southern California would face much greater increases in energy costs than northern California. Also, because it is low lying and heavily developed, southern California is more vulnerable to sea level rise than northern California,

although San Francisco Bay is also quite vulnerable. Furthermore, the Sacramento region is at particular risk from increased flooding.

The effects of climate change on ecosystems are likely to be far reaching and dramatic across the state. The location and productivity of terrestrial vegetation and wildlife that depends on it will change quite substantially. Forests could become grasslands or shrublands could become woody. Certain habitats such as alpine and Mediterranean shrubland could largely reduced. Diversity of vegetation communities could also be reduced. If California is wetter and mildly warmer, then productivity could rise and community biodiversity maintained. Drier conditions will result in reduced productivity and biodiversity. Much warmer conditions can reduce biodiversity as well. Fire is likely to increase whether it is wetter or drier. California's natural systems could be quite different from what they are today.

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Glossary

CSS	Coastal Sage Scrub
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
GAP	California Gap Analysis Project
GCM	General Circulation Model
GIS	Geographic Information System
HadCM2	Hadley Climate Model, version 2
NAST	U.S. National Assessment Synthesis Team
NCAR	National Center for Atmospheric Research
NPP	Net Primary Productivity
PCM	Parallel Climate Model
PIER	Public Interest Energy Research
RCM	Regional Climate Model
SWAP	Statewide Water Agricultural Production Model
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey

Appendix I

**Climate Scenarios for a California Energy Commission Study of the Potential Effects of
Climate Change on California: Summary of a June 12-13, 2000, Workshop**

Attachment A: Workshop Agenda for California Climate Scenarios Workshop

Attachment B: Preliminary List of Workshop Attendees and Contact Information

Attachment C: Communication from Stephen Schneider

Attachment D: A Description of the Processes Involved in the Creation of Transient
California Climate

Appendix II

Baseline Scenarios for a California Energy Commission Study of the Potential Effects of Climate Change on California: Summary of a June 12, 2000, Workshop

Attachment: List of Participants and Contact Information

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How We Will Grow: Baseline Projections of California's Urban Footprint through 2100

Attachment A: Projected Population Growth

Attachment B: Urban Land Shares, Incremental Densities, Infill Shares, Greenfield
Population, and Urban Acreage

Appendix IV
Climate Change Effects on Vegetation Distribution, Carbon Stocks, and Fire Regimes
in California

Attachment: The Simulated Ecosystem Response to the Incremental Future Climate
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Appendix V

Climate Change and Urbanization in California: Potential Effects on the Extent and Distribution of Major Vegetation Community Types

Appendix VI
Climate Change and California Ecosystems: Potential Impacts and Adaptation Options

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Attachment B: Agenda for Commission/EPRI Climate Change Adaptation Workshop

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Attachment C: Hydropower in the CALVIN Model

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Climate Change Sensitivity Study of California Hydrology

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The Effects of Climate Change on Yields and Water Use of Major California Crops

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Appendix X

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Attachment B: Change in Cropping Pattern by Crop for 2100 Runs – Graphical Representation

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The Impact of Climate Change on Energy Expenditures in California

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A California Model of Climate Change Impacts on Timber Markets

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Evaluation of California Health Data in Relation to El Niño Patterns

Appendix XV
Summary of Other Types of Ecological Effects

Appendix XVI

Summary of Benefits from Commission Funding of EPRI's Collaborative Climate Research Program 1998-2002